Norwegian University
of Life Sciences

Master's Thesis 2018 30 ECTS
Faculty of Science and Technology
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Assessment of yield point methods in monotonic and cyclic load tests: An experimental investigation of mechanical fasteners in solid wood panel

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ABSTRACT

Nowadays, there are several proposed methods of deciding the yield point when calculating the results from an experimental research on timber structures with mechanical fasteners. How does this affect the analysis of the timber product and how are these methods compatible with today's possibility of computer programmes to calculate results? For this thesis, these questions served as guidelines during a product test, testing different configurations on sill connectors in solid wood panel with monotonic and cyclic load test. Results have been calculated from three different yield point methods, using the Yasumura and Kawai (Y&K) method, method (b) from NS-EN 12512 (2002) and the EEEP curve method. These methods are compared to evaluate their effect on the ductility value of the product. In addition, were the calculations done with the software programme R, checking how adaptable these yield point methods are.

This thesis is divided into two phases. First, an experimental phase and second, a calculation phase. The experimental phase consists of three stages where the first stage was the preparation of the experiment, the second was the assembly of the specimens and lastly the testing stage. For the calculation phase was a draft proposal of the revision on NS-EN 12512 accessible, facilitating a review of the proposal draft. Furthermore, an R script was written for each study divided by the three standards that where calculated (i.e. NS-ISO 6891 (1991), NS-EN 12512 (2002) and EN 12512 (2018) Draft proposal Version n°20180410). A comparison of standards was derived from the calculations, which includes a view on how they affect the stiffness, yield point and ductility values of the tested product.

The evaluation of the different methods shows the same trends as discussed from literature. The results retrieved from the calculations used by the newest proposal draft shows approximately the same ductility values in cyclic load tests than what the results from the current standard yields. In addition, was the runtime for the R script when calculating with the EEEP curve method much more efficient than for other methods.

The R script for each study is included as an attachment, while a scripted version verified on an external dataset is inserted in the appendix.

ACKNOWLEDGEMENTS

I wish to acknowledge my deepest gratitude to professor Roberto Tomasi, my thesis supervisor, for his professional guidance and valuable support during my MSc thesis project. I would also like to thank professor Olav Høibø at the Faculty of Environmental Sciences and Natural Resource Management, for his advice and assistance during the experimental phase of this thesis.

My grateful thanks go also to Mr. Roar Økseter for his time assisting me in the laboratory and Mr. Arne Svendsen and the staff at the steel laboratory at NMBU for constructing steel material needed for the experimental phase of this project. Your kindness and effective work was very valuable for me and the conduction of the experiment.

I would also like to extend my thanks to Mr. Jørgen Beitdokken and the staff at Termowood AS for providing with the Termowood material, equipment needed to assemble the specimens and guidance on how to use a nail gun.

Finally, I wish to thank my family and closest friends for the support and continuous encouragement throughout my years of study and during the process of working and writing this thesis. A special thanks to my boyfriend, who accompanied me with the assembling of over 150 specimens and cheering me on during the project.

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LIST OF ABBREVIATIONS

D	ductility of joint
d	diameter of connector
EC8	Eurocode 8 – NS-EN 1998-1-1
E_d	Dissipated energy of a full cycle in cyclic load test
E_p	Available potential energy
F	Force
F_{est}	Estimated maximum force
F_{max}	Maximum load
F_{III}	Maximum load of the third cycle in cyclic load test
F_u	Ultimate load
F_y	Yield load
$f_{ax,k}$	Characteristic withdrawal capacity
$f_{h,k}$	Characteristic embedding strength
K_{ser} / K	Slip modulus or initial stiffness
$M_{y,Rk}$	Characteristic yielding moment of the fasteners
P_{max}	Maximum peak load reach during load test
P_y	Yield load used for EEEP curve calculation
SWP	Solid Wood Panel
TW	Termowood
t	Penetration length of the fasteners
V / v / u	Displacement/slip
V_u / v_u / u_u	Ultimate displacement/slip
V_y / v_y / u_y	Yield displacement/slip
$w_{failure}$	Area under the load-displacement curve
β_{sd}	Design strength degradation factor
$\Delta_{failure}$	Displacement at failure
γ_{Rd}	Overstrength factor
μ	Ductility ratio
ν_{eq}	Equivalent viscous damping ratio
$\nu_{eq,III}$	Equivalent viscous damping ratio of the third cycle in cyclic load test

1 INTRODUCTION

The thesis sprung out of a product test on behalf of Termowood AS. From a practical standpoint, it was of interest to test the sill connector and the vertical connection of their product to get a picture of how it behaves. From an academic point of view, NMBU was also interesting to check the sill connectors with different configurations, compared to the product in use. As a result, this became the build-up for an experimental investigation. Furthermore, the academic discussion about different calculation methods arose as an area of interest during the retrieval of test results. This provided a motivation to conduct a cyclic load test in addition to the monotonical load test initially agreed with Termowood AS. Moreover, there was a possibility of receiving a draft proposal of the revision to NS-EN 12512 (2002). In sum, the main focus of the thesis is to compare different calculation method used on monotonic and cyclic load tests on timber structures with mechanical fasteners.

According to the current definition of static ductility given in NS-EN 1998-1 (2004) (EC8), that is the ratio between the ultimate displacement and the yield displacement of a structure, it is shown that different calculation methods for the yield point and the ductility ratio used around the world, deviates. This may influence the determination of the ductility category given in EC8 for ductility class medium (DCM) and high (DCH). The new draft proposal EN 12512 (2018) version n°20180410 defines new yield point definitions and ductility ratio then what the current standard holds. It is therefore important to compare results calculated from these two standards. The new proposal draft will henceforth be referred to as EN 12512 (2018) Draft.

The calculations done for this thesis is achieved with the statistical and graphical software program R, which provides a wide variety of statistical and graphical techniques and is a program with effective data handling.

The standards used in this thesis are the following:

- NS-EN 1995-1-1 2004. Design of timber structures - Part 1-1: General Common rules and rules for buildings. *Eurocode 5.* Norwegian Standard.
- NS-ISO 6891 1991. Timber Structures, Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics. *In:* EN 26891:1991 (ed.). Norwegian Standard.
- NS-EN 12512 2002. Timber Structure, Test Methods - Cyclic testing of joints made with mechanical fasteners.: Norwegian Standard.
- EN 12512 2018. Proposal draft Version n°20180410: Timber Structures - Test Methods - Cyclic testing of timber connections and assemblages for seimic design. *In:* Daniele Casagrande CNR-IVALSA Italy & Maurizio Piazza University of Trento Italy (ed.).

2 LITERATURE

In this chapter, a brief description on capacity design and ductility is presented as well as an introduction of the current view based on a selection of different yield point methods. The following three standards NS-ISO 6891 (1991), NS-EN 12512 (2002) and EN 12512 (2018) Draft proposal are explained in detail including their testing protocols and calculation methods. In addition, three yield point methods are presented (i.e. Yasumura and Kawai method, the NS-EN 12512 (2002) method and the EEEP curve method), along with a literature review.

2.1 Capacity Design, Ductility and Yield Point methods

Capacity based design and ductility are essential components for a proper structural design in seismic areas. The main purpose of the approache is to design the structure to be certain that when failure happens, the structure fails in a ductile manner. One of the reasons to design a ductile structure is to ensure that failure will occur with large deformations before collapse, meaning that the occupants of the structure can be warned in the case of an unexpected load (e.g. exceptional snow load). In other words, the capacity based design is where the *brittle* member of a structure is given a higher design strength capacity than the *ductile* member in the same structure. Since timber is considered a brittle material, it is likely to only develop ductility in the connections. In essence, the connections need to behave in a ductile manner and the timber materials design strength capacity must be higher than that of the connectors (Jorissen and Fragiacomo, 2011). The concept of the design strength capacity of a structural member is as follows:

$$R_{i,Rd} = \frac{k_{mod} \cdot R_{i,Rk}}{\gamma_M} \tag{1}$$

Where $R_{i,Rk}$ is the characteristic resistance value of the member, k_{mod} is the modification factor for load duration and moisture content of the timber, and γ_M is the partial material factor.

To ensure a structure that follows the capacity-based design, in which the brittle members design strength must be higher than that of the ductile member, the following equation must be satisfied:

$$R_{b,Rd} \geq \gamma_{\mathrm{Rd}} \cdot R_{d,Rd} \tag{2}$$

Where $R_{b,Rd}$ and $R_{d,Rd}$ are the design strength capacity for brittle and ductile member respectively and γ_{Rd} is the overstrength factor.

Follesa et al. (2018) presents the latest revision of the EC8 chapter 8, where they show that the new proposal of capacity design includes a reduction factor for strength degradation, β_{sd} due to cyclic loading. The equation is as follows:

$$R_{b,Rd} \geq \frac{\gamma_{Rd}}{\beta_{sd}} \cdot R_{d,Rd} \tag{3}$$

Strength degradation is the reduction factor in strength during a cyclic load test. The new proposal NS-EN 12512 (2018) Draft presents the degradation factor in their calculation proposal, which is not the case for the current standards NS-EN 12512 (2002) and EC8.

NS-EN 12512 (2002) defines the ductility to be the connections ability to undergo large deformations in the plastic range without a substantial reduction in strength. This value designates for instance, how well an assembly will endure large lateral displacements imposed by earthquake. The classification of ductility is retrieved from EC8 and is given in table 2-1.

Table 2-1: classification of ductility according to NS-EN 1998-1 (2004).

Classification	Static ductility ratio
Low ductility	$\mu \leq 4$
Medium ductility	$4 \leq \mu \leq 6$
High ductility	$\mu \geq 6$

Based on Stehn and Björnfot (2002), there are several ways of defining the ductility, in which they present twelve different ductility definitions. It shows that NS-EN 12512 (2002) has incorporated the relative definition of ductility, which requires the calculation of the so-called yield slip, ν_y (also referred to as u_y). This implies that ductility is the ratio between the ultimate displacement and the yield displacement, estimated from where the connection begins to yield.

To determine the yield point, there are different methods that exists for timber structures, and as stated from Muñoz et al. (2008), the methods lack harmony. Some of the yield point methods discussed in Muñoz et al. (2008) that will be used in this thesis, are the European bilinear elastic-plastic approach, used in NS-EN 12512 (2002) (also referred to as method (b) / CEN / 1/6 procedure), the Equivalent Energy Elastic-Plastic curve (EEEP) procedure, and the Yasumura and Kawai (Y&K) procedure. Each one of them will be described in more detail below. Other procedures that Muñoz et al. (2008) mentions are the Karacabeyli and Cecotti procedure, Commonwealth Scientific and Industrial Research Organisations (CSIRO) procedure and the 5% diameter offset procedure. Each one of these methods can give different yield point estimations on the same connection, which can lead to an over- or under-estimation of the ductility ratio, hence a misclassification of connections in ductility categories. The three yield point methods (i.e. EEEP, Y&K and 1/6 method) will be calculated, to evaluate how it affects the Termowood products ductility values.

Results from Muñoz et al. (2008) showed that the yield point method retrieved from the EEEP curve always was higher and located off the load-displacement curve while the CSIRO method tended to be lower than the other methods. Studies resulting in connections with a low initial stiffness, the yield points from CEN were located off the curve and K&C yield point were in the plastic range. The other methods such as Y&K and 5% diameter offset had smaller differences among each other.

2.2 Norwegian and European Standards

The experiments for this thesis, testing the mechanical fasteners in Termowood product in monotonic load and cyclic load, follows the Norwegian standards NS-ISO 6891 (1991) and NS-EN 12512 (2002) respectively. The standards, including relevant calculations, are presented in the chapter. The proposal draft from EN 12512 (2018) standard, version 20180410 is also included in the thesis. How the standards are incorporated to each test are described in detail in chapter 3.2 *Experimental Investigation.*

2.2.1 NS-ISO 6891 (1991)

NS-ISO 6891 (1991) – *Timber Structures, Joints made with mechanical fasteners – General principles for the determination of strength and deformation characteristics* is adopted from the International Standard (EN 26891) and serves as a guideline to enable comparability of results across laboratories.

A specific load procedure described in the standard was applied to all the monotonic tests. The procedure contains a pre-loading cycle followed by a complete load-to-break stage, henceforth preload stage and main-load stage respectively.

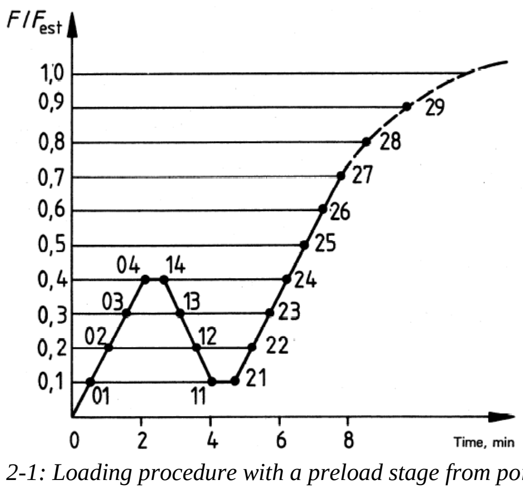


Figure 2-1: Loading procedure with a preload stage from point 01 to 11 and then a complete load to breakage stage from point 21. Source from NS-ISO 6891-1991 page 3.

The load procedure in figure 2-1 shows the preload stage from point 01 to 11 and continues with the main-load stage from point 21 and further on. The preload stage is conducted by applying load up to $0,4 \cdot F_{est}$, then stopped and maintained for 30 seconds. It proceeds by reducing the load to $0,1 \cdot F_{est}$ where the load is also maintained for 30 seconds. Thereafter, the complete main-load stage begins. The purpose of the preload stage is for the connectors to settle into the material, reducing possible deviations in the results.

F_{est} is the estimated maximum load and shall be determined on the basis of calculations or preliminary tests before conducting the experiments. Adjustments of F_{est} is described in section 8.6 in NS-ISO 6891 (1991) and will be discussed in chapter 3.2 *Experimental Investigation.* Furthermore, the maximum force, F_{max}, is obtained after the experiment is conducted, which is the maximum load reached before or at a displacement of 15 mm.

The yield slip is referred to as the *elastic slip* in the standard and is calculated from displacements retrieved between the preload stage and main-load stage. This method of calculating the yield slip is henceforth referred to as the ISO-procedure. The calculations of following values are determined from NS-ISO 6891 (1991) – 8.5.

Modified initial slip:

$$v_{i,mod} = \frac{4}{3}(v_{04} - v_{01}) \qquad (4)$$

Elastic slip (ISO-procedure):

$$v_e = \frac{2}{3}(v_{14} + v_{24} - v_{11} - v_{21}) \qquad (5)$$

Slip modulus:

$$k_s = \frac{0{,}4 \cdot F_{est}}{v_{i,mod}} \qquad (6)$$

2.2.2 NS-EN 12512 (2002)

The cyclic load test follows the Norwegian standard NS-EN 12512 (2002) – *Timber structures, Test methods – Cyclic testing of joints made with mechanical fasteners.* Cyclic load test is a test where the load is applied in both compression and tension on the same specimen during a test run. The test will first push on the specimen with compression force until a specified deflection is reached and then pulls back with tension force to another deflection point. This loading procedure continues in cycles with increasing deflections until failure or a displacement of 30 mm is reached.

The cyclic load test provides information about the mechanical fasteners ductility, dissipation of energy and impairment of strength, which is valuable for structures in seismic regions.

The standard conditionings required for the specimen is the standard atmosphere 20/65, according to ISO 554. The moisture content was measured after testing and the same procedure was followed for monotonic load test with the same instruments. This is further explained in detail in chapter 3.2.1 *Procedure for The Monotonic Load Test*

The estimated yield slip, $V_{y,est}$, can be retrieved from either calculations or from the monotonic load tests, implying that the monotonic load test should be completed before the cyclic load test. The estimated yield slip outcome will be further explained in chapter 3.2 *Experimental Investigation.*

The complete procedure explaining the cyclic load test, visualized in figure 2-2, is regulated by the standards section 6.4.2. The test is initiated in compressive load until it reaches 25 % of the estimated yield slip, $V_{y,est}$, followed by a tension load, pulling up to reach 25 % estimated yield slip in the opposite direction. This cycle continues with an increase in the percentage of the estimated yield slip for each cycle. On the third cycle and beyond, the cycle will contain a set of three cycles with the same amplitude, henceforth called a cycle set. The cycles continue until the limit of 30 mm is reached or failure occur.

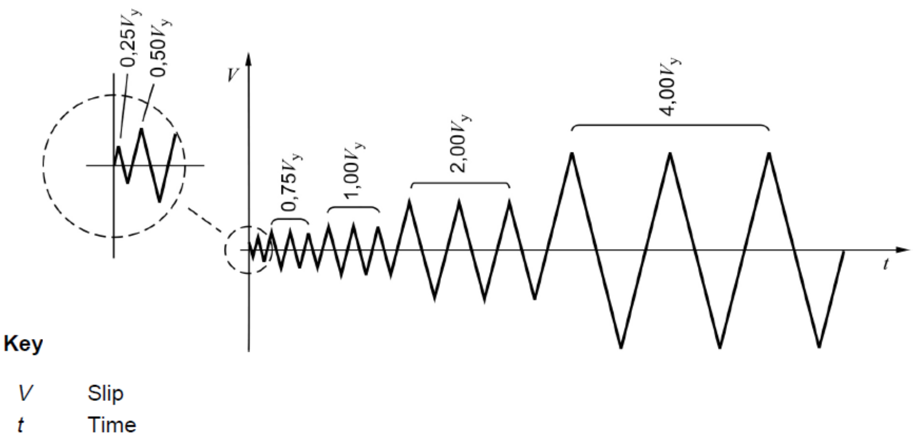


Figure 2-2: Procedure for cyclic testing (Complete procedure). Source: NS-EN 12512 fig.5 page 12.

The following values are described and explained from NS-EN 12512 (2002) – section 3 *Terms and definitions.*

Maximum load – Maximum load reached during test, F_{max}

Yield point – The intersection between two lines drawn from the load-displacement curve. There are two methods, namely method (a) and (b). The first method is used when the load-displacement curve has two well-defined linear parts, where the yield point is retrieved by the intersection of two lines drawn from these two linear parts (Figure 2-3).

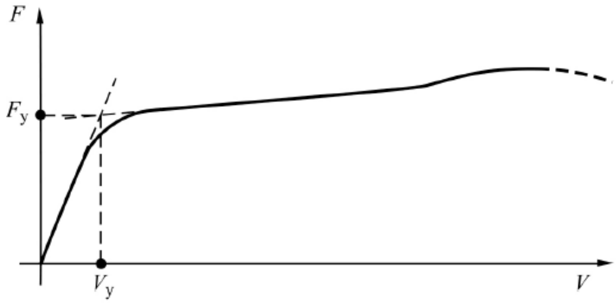


Figure 2-3: Definition of yield point used with method (a).
Source: NS-EN 12512 (2002, pp. 7 - figure 1a)

Method (b) however, is when the load-displacement curve does not have two well-defined linear parts. The first line is drawn through the points of 10% F_{max} and 40% F_{max}. The second line shall have a slope of 1/6 of the first lines slope, as well as it tangents the graph. The yield load and slip are then retrieved at the intersection between these two lines. The definition is shown in figure 2-4, and this procedure for calculating yield load and slip is henceforth named 1/6 procedure.

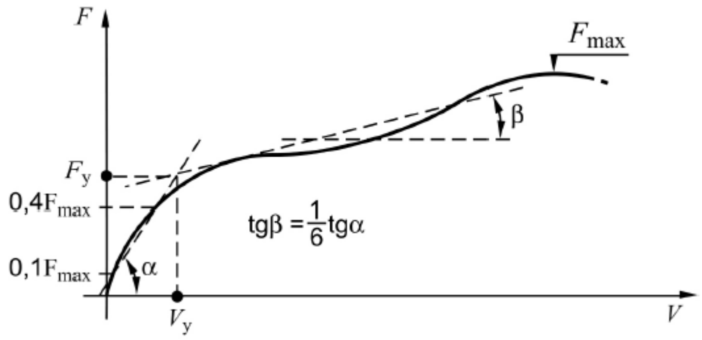


Figure 2-4: Definition of yield load and yield slip after NS-EN 12512 (2002) 1/6 procedure.
Source: NS-EN 12512 (2002) figure 1b.

Ultimate load/slip – The load that corresponds to the following three arguments, whichever occurs first: failure; 80%F_{max} for a slip of less than 30 mm; or slip of 30 mm. The corresponding displacement for the ultimate load is the ultimate slip.

Slip modulus – NS-EN 12512 (2002) do not point out how to calculate the slip modulus, however the slip modulus is the ratio between yield load and yield slip, therefore is it possible to retrieve the slip modulus by dividing the yield load with the yield slip.

The standard states that the above definitions referred to cyclic load-displacement envelope curve may also be used for monotonic load-displacement curves.

Ductility – Describes the mechanical fasteners ability to undergo large changes in plastic displacement without losing any big amount of strength. The ductility is calculated as the ratio between ultimate slip and yield slip.

$$D = \frac{V_u}{V_y} \tag{7}$$

Impairment of strength – The reduction in load between the first and the third cycle of the same amplitude in a cycle set. Calculated for both tension and compression side, namely called ΔF_t and ΔF_c respectively. Figure 2-5 shows the definition of impairment strength.

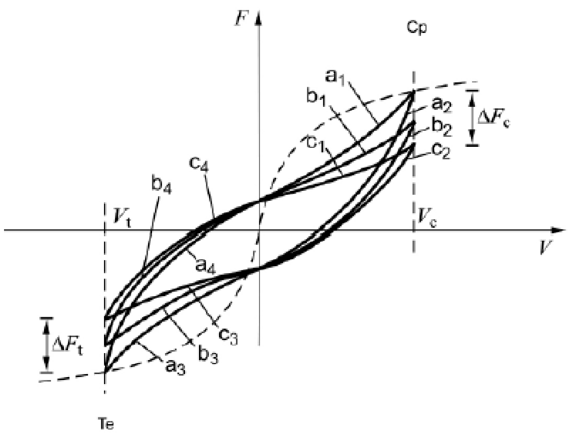


Figure 2-5: Definition of impairment of strength.
Source: NS-EN 12512 (2002) figure 3.

Dissipation of energy – The equivalent viscous damping ratio is measured by hysteresis. It is measured from the ratio between dissipated energy, E_d, and potential energy, E_p. As shown in figure 2-6, the dissipated energy is calculated as the area in one half cycle, and the available potential energy as the area of the triangle where the corners are zero displacement, maximum displacement and maximum load for the given half cycle. The equivalent viscous damping ratio is then given as,

$$\nu_{eq} = \frac{E_d}{2\pi \cdot E_p} \tag{8}$$

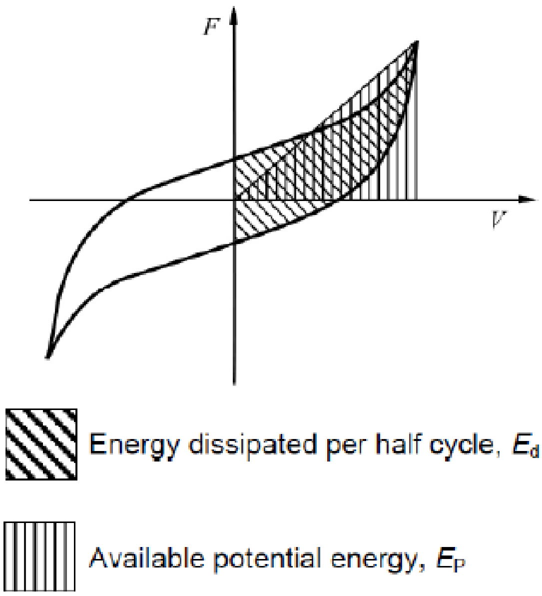


Figure 2-6: Equivalent viscous damping ratio for one cycle.
Source: NS-EN 12512 (2002) figure 4.

2.2.3 EN 12512 (2018) Draft Version n°20180410

This is a proposal for the revision of EN 12512 (2002) proposed by Daniele Casagrande for CNR-IVALSA in Italy and Maurizio Piazza for University of Trento in Italy. The proposal suggests other calculation methods then what the NS-EN 12512 (2002) now holds. The proposal also suggests specific calculation methods for monotonic load test as well. Therefore, the calculation methods for monotonic load test stated from the draft has also been calculated for in this thesis. A description of the calculation methods for the new proposal are presented below.

The draft proposal provides a different loading protocol for conducting the cyclic load test than NS-EN 12512 (2002). This thesis will not investigate the differences between loading protocols, but rather focus on the calculation methods. In practical terms, the experiment for cyclic load test follows the NS-EN 12512 (2002) loading protocol.

Cyclic load test

Load Envelope Curve (LEC) – A curve connected by the maximum load in each cycle. 1st LEC corresponding to maximum load in every first cycle in each cycle set, 2nd LEC corresponding to maximum loads in every second cycle in each cycle set and 3rd LEC corresponding to the third cycle. Values between load segments are obtained with linear interpolation.

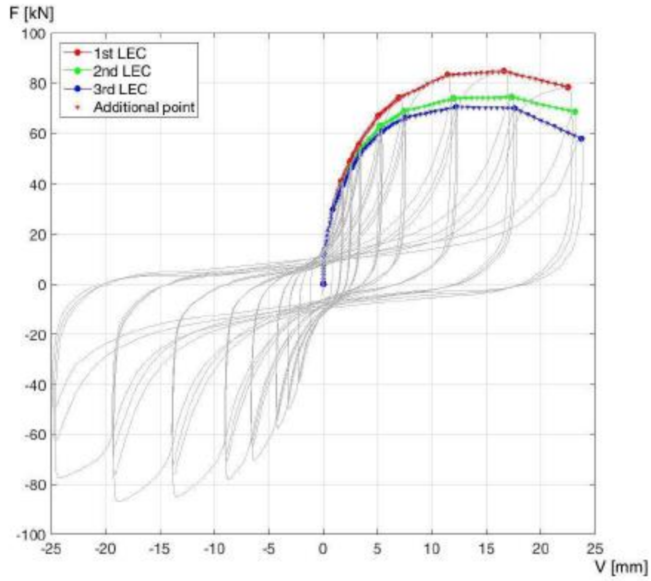


Figure 2-7: Definition of Load Envelope Curve (LEC).
Source:EN 12512 (2018figure 1).

Peak Load – The maximum load on 1st LEC reached during cycle test.

Ultimate load/slip – The displacement corresponding to the three following arguments, whichever occurs first is the ultimate slip: failure; 80% Peak load retrieved from the 1st LEC after the peak load; or strength degradation factor, β(ν) – lower than or equal to β_{min}. The corresponding load retrieved at the ultimate slip is the ultimate load. β_{min} is a coefficient that must not be lower than 0,60 for mechanical connectors, for this thesis the coefficient is set at 0,75.

Strength degradation factor – The ratio between the loads in the 1st and the 3rd LEC. The loads evaluated must be at the same displacement value when divided on each other. The following equation for the strength degradation factor is given as,

$$\beta(\nu) = \frac{F_3(\nu)}{F_1(\nu)} \leq 1 \tag{9}$$

Design strength degradation factor – The minimum strength degradation factor, evaluated by displacements lower than the ultimate slip. The design strength degradation factor, β_{sd} shall be higher than or equal to β_{min}.

$$\beta_{sd} = \min[\beta(\nu < \nu_u)] \geq \beta_{\min} \tag{10}$$

Maximum load – The maximum load retrieved from the 1st LEC for displacements lower than or equal to the ultimate slip.

Equivalent Energy Elastic-Plastic (EEEP) Curve – The EEEP curve circumscribes an area which is equal to the area under the 1st LEC, with boundaries from zero displacement to ultimate slip. Figure 2-8 shows a description of the EEEP curve. The first line that describe the EEEP curve goes through the points at 10% and 40% of the maximum load, while the second line is the horizontal line positioned so that the area of EEEP curve abides the area of the 1st LEC. The lines are shown as blue lines in figure 2-8.

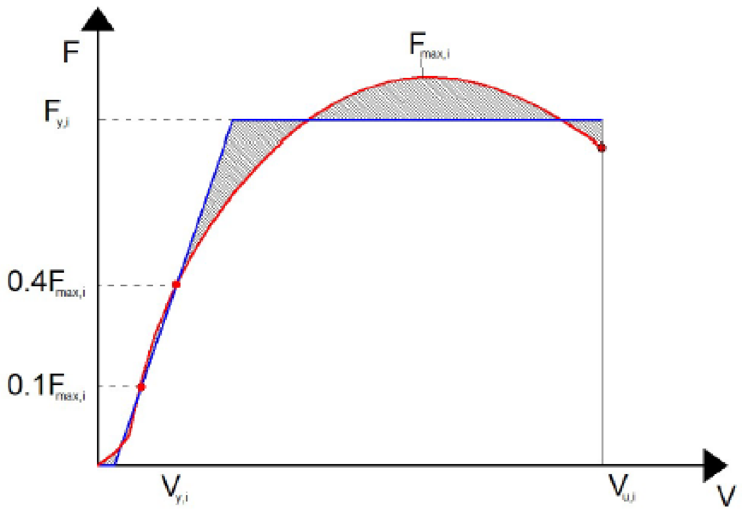


Figure 2-8: Definition of the EEEP curve (blue) with 1st LEC (red). Source: EN 12512 (2018) Draft figure 6b.

Slip modulus – The slope of the line that goes through the points 10% and 40% of the maximum load in the 1st LEC.

Yield point – The point where the horizontal line of the EEEP curve and the line described in slip modulus intersect. This procedure to find yield load and yield slip are henceforth called the EEEP procedure.

Ductility – The ratio between the ultimate slip and yield slip. The same definition as from NS-EN 12512 (2002).

Dissipation of energy – The equivalent viscous damping ratio is measured by hysteresis and is the ratio between dissipated energy, E_d, and potential energy, E_p. The dissipated energy is calculated as the area in one entire cycle while the available potential energy is the area of the triangle where the corners are the positive values of zero displacement, maximum displacement and maximum load for the given cycle. Their definition is shown in figure 2-9. The equivalent viscous damping ratio is then given as,

$$\nu_{eq,c} = \frac{E_d}{4\pi \cdot E_p} \tag{11}$$

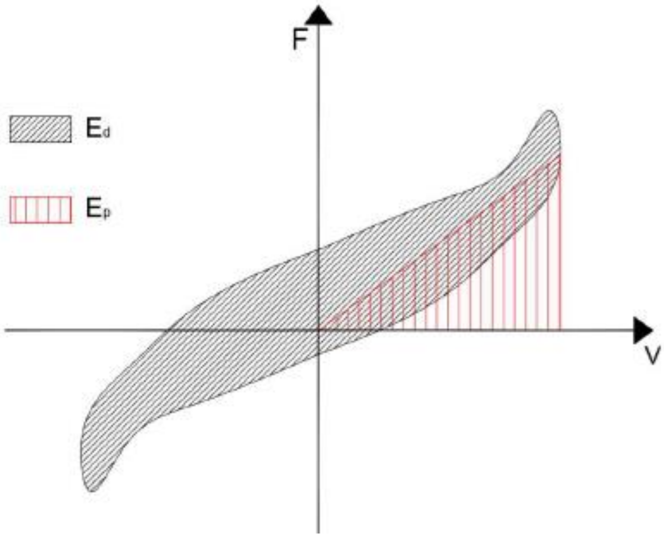


Figure 2-9: Definition of equivalent viscous damping ratio according to the new standard proposal. Source: EN 12512 (2018) Draft version n°20180410 figure 5.

Monotonic load test

Peak Load – The maximum load reached during monotonic test

Ultimate load/slip – The displacement corresponding to the three following arguments, whichever occurs first is the ultimate slip: failure; 80% Peak load for the position after the peak load; or 30 mm slip. The corresponding load for ultimate slip is the ultimate load.

Maximum load – The maximum load reached for displacement lower than or equal to the ultimate slip.

Slip modulus – The slope of the line that goes through the points 10% and 40% of the maximum load in the load-displacement graph.

Yield point – As explained for cyclic load test above, is the yield load and yield slip retrieved from the point where the horizontal line of the EEEP curve and the line described in slip modulus intersect. This definition also applies for the monotonic load test, where the 1st LEC corresponds to the monotonic load-displacement curve.

2.3 Different yield point methods

In this chapter, an overview of the discussions on different yield point methods from the literature will be presented briefly. Afterward will the results of each calculation methods be presented in the result chapter and thereafter be discussed and compared to each other in the discussion chapter.

2.3.1 NS-EN 12512 (2002) yield point method

Piazza et al. (2011) discusses the yield point calculation approach from NS-EN 12512 (2002), where the two approaches called method (a) and (b) depends on the shape of the load-displacement curve. Method (a) is used when the load-displacement curve is displayed with two well-defined linear parts, while method (b) is applicable when the curve does not have a well-defined linear part and the 1/6 procedure is being used.

The issue that Piazza et al. (2011) discuss based on the methods is the uncertainty of selecting the one over the other, when the linear parts of the load-displacement curves are not that apparent. Besides, the yield values obtained from each method gives very different results when calculating on the same specimen. When Piazza et al. compared these two methods on their experimental results for nails, the 1/6 procedure obtained much lower yield point than method (a). It is worth noting that method (a) involves uncertainty, in terms of where to define the straight lines.

Piazza et al. (2011) applies a procedure called the Foschi model (Foschi, 1974) which allows for a more analytical approach that is more compatible with computerized procedure. The Foschi model contains three equations determining the relationship between the force F and the displacement ν. The model has an acceptable accuracy rate between the result for nail and dowel connectors compared to method (a). Therefore, Foschi model might be a better solution when one needs a procedure that fits a computerized process. However, this only applies when the load-displacement curve has two well-defined linear parts. In situations where the load-displacement curve does not have two well-defined linear parts, the 1/6 procedure and the Foschi model were not sufficiently accurate when compared for experiments on bolt and screw connections.

Piazza et al. concludes that it is not possible to define a common method to describe the post-elastic properties of timber-to-timber connections. They suggest that the two procedures, method (a), and a mix between the 1/6 procedure and Foschi model, should be followed separately for each nail/dowel- and screw/bolt connections. As a consequence of the uncertainties, giving different yield point results will affect the characterization of the ductility values. However, the Foschi model will not be addressed any further.

Meanwhile, Yasumura (1998) compares the 1/6 procedure with the yield point calculations from 5% diameter offset on experiments with dowel type joints. The study found yield point calculations from the 1/6 procedure showed to align with those from the 5% diameter offset method, which was also the case for the calculated yield theory for the bolted joints.

2.3.2 Yasumura & Kawai yield point method

The procedure was proposed for the evaluation of wood frame shear walls by Yasumura and Kawai (1997) and has been adopted by others for calculating the yield point and stiffness values from a load-displacement curve (Fragiacomo et al., 2011). Yasumura and Kawai suggests drawing the first line the same way as 1/6 procedure from NS-EN 12512 (2002), as drawing it through the points of 10% F_{max} and 40% F_{max}. The second line is suggested differently, where it is drawn through points corresponding to 40% F_{max} and 90% F_{max} and is then moved so that the line is tangent to the load-displacement curve. The line must have the same inclination after it has been moved tangentially (i.e. the moved line must be parallel to the original drawn line). The intersection between the two lines gives the yield load. To retrieve the yield slip, the yield point must be projected horizontally onto the load-displacement curve. The initial stiffness is the slope of the first drawn line through 10% and 40% F_{max}. Figure 2-10 visualize a description of the method.

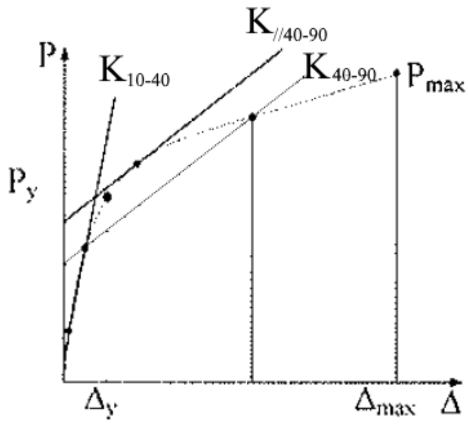


Figure 2-10: Yasumura & Kawai procedure to find the yield point.
Source: Muñoz et al. (2008, pp. 4, Figure 2(d))

2.3.3 EEEP curve – yield point method

This method was originally proposed for concrete and steel structures (Foliente, 1996), and is the ideal EEEP curve which is describe earlier in chapter 2.2.3 *Cyclic load test.* As stated earlier, the EEEP curve is derived such that the area under the curve is equal to the area under the load-displacement curve. The equation for yield load is based on Muñoz et al. (2008) (i.e. the horizontal line of the EEEP curve). The equation is as follows:

$$P_y = \left[\Delta_{failure} - \sqrt{\left(\Delta_{failure}^2 - \frac{2w_{failure}}{K}\right)}\right] \cdot K \qquad (12)$$

Where P_y is the yield load, $w_{failure}$ is the area under the load-displacement graph from the origin to failure displacement, $\Delta_{failure}$ is displacement at failure or ultimate slip and K is the stiffness retrieved as the slope of the diagonal line. Figure 2-11 includes EEEP curve and the description of each variables from the equation.

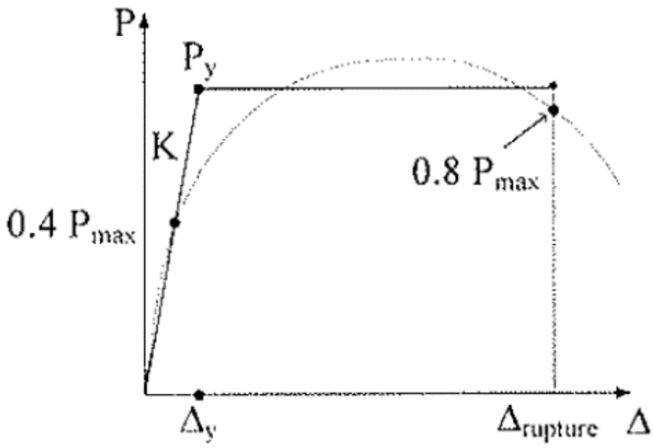


Figure 2-11: EEEP curve procedure to find the yield point.
Source: Muñoz et al. (2008, pp. 4, Figure 2(c))

3 EXPERIMENTAL ANALYSIS OF TERMOWOOD CONNECTIONS

The experimental process for the Termowood product is described in detail in this chapter. The experiment is divided into three study groups, where each study addresse different forces acted on a shear wall. The results from the experiment are found in chapter 4 *Results.*

In the first section, the materials used in all the test specimen are described. In addition, mechanical properties, geometry and photos is represented. A continuation of the discussion can be found in the experimental configuration section.

3.1 Materials

3.1.1 Termowood Element

The Termowood (TW) element is made of two Solid Wood Panels (SWP), which is panels that are cross laminated, much like CLT, but with a smaller cross section. The SWP in the elements is 40 mm thick, three-layered wood panel with tongue and groove system. The two SWP panels are combined with wood dowels in the middle and then filled with insulation. A thorough description of the properties of SWP is presented later in the chapter.

The concept of the product is to be time- and cost-saving during the assembling at construction site. Figure 3-1 show a picture of the product without insulation. The tongue and groove system at each side of the SWP panel, which works as a vertical connection between each TW element.

Figure 3-1: Termowood element.

3.1.2 Screws

5,0x90mm

Screws tested and used in assembling sills is a wood screw with external coating C4, partially threaded, type 17 point and with a size equal to 5,0x90mm (figure 3-2). Characteristic parameters for the fastener is shown in table 3-1.

Figure 3-2: Wood screw 5,0x90mm used in study 1 and 2.
Source: Motek (a) (2018)

Table 3-1: Characteristic parameters for wood screws 5,0x90mm. Source:Motek (a) (2018)

Characteristic parameters			
Screw Diameter	d	5,0	*mm*
Screw Length	L	90,0	*mm*
Screw threaded length	L_1	54,0	*mm*
Characteristic Withdrawal Parameter (Density 400kg/m^3)	$f_{ax,k}$	16,18	*N/mm^2*
Characteristic Head Pull-Through Parameter (Density 400kg/m^3)	$f_{head,k}$	18,58	*N/mm^2*
Characteristic Yield Moment	$M_{y,k}$	8562	*Nmm*
Max torsion moment	$f_{tor,k}$	3,05	*Nm*
Characteristic Tension Load		7,76	*kN*

4,2x51mm

The vertical connection between each TW element tested with fasteners for one test study. The fasteners used in the particular study is a smaller wood screw, without external coating, fully threaded, type 17 point and with a size equal to 4,2x51mm (figure 3-3). Table 3-2 presents the characteristic parameters for the fastener.

Figure 3-3: Wood screw 4,2x51mm used in study 3.

Table 3-2: Characteristic parameters for screws 4,2x51mm. Source: Motek (b) (2018)

Characteristic parameters			
Screw Diameter	*d*	4,2	*mm*
Screw Length	*L*	51,0	*mm*
Characteristic Withdrawal Parameter (Density 450kg/m^3)	$f_{ax,k}$	17,3	N/mm^2
Characteristic Head Pull-Through Parameter (Density 450kg/m^3)	$f_{head,k}$	20,2	N/mm^2
Characteristic Yield Moment	$M_{y,k}$	3652	*Nmm*
Max torsion moment	$f_{tor,k}$	3,55	*Nm*
Characteristic Tension Load		5,98	*kN*

3.1.3 Nails

Nails tested and used for assembling sills are 3,1x90mm diamond coated, barbed shank, used with nail gun (Figure 3-4).

Figure 3-4: Nails 3,1x90mm. Source: Motek (c) (2018)

The diamond coated cover works as a glue. When pushed into the wood, the friction melts the coated cover, giving the nails a 20 % higher withdrawal capacity. The characteristic parameters are shown in table 3-3.

Table 3-3: Characteristic parameters for nails. Source: Motek (c) (2018)

Characteristic parameters			
Nail Diameter	*d*	3,1	*mm*
Nail Length	*L*	90,0	*mm*
Material Wire Tensile Strength (EN10016-2)	f_u	600	N/mm^2
Characteristic Withdrawal Parameter	$f_{ax,k}$	7,61	N/mm^2
Characteristic Head Pull-Through Parameter	$f_{head,k}$	16,88	N/mm^2
Characteristic Yield Moment	$M_{y,k}$	3480	*N/mm*

3.1.4 Sills

Some of the specimen are assembled with a top/bottom and a middle-sill. These sills represent the top-, bottom- and middle-sills used at construction site. The TW element is connected to the middle sill, where the sill serves as a framework for the walls. Figure 3-5 shows the construction details of a TW wall.

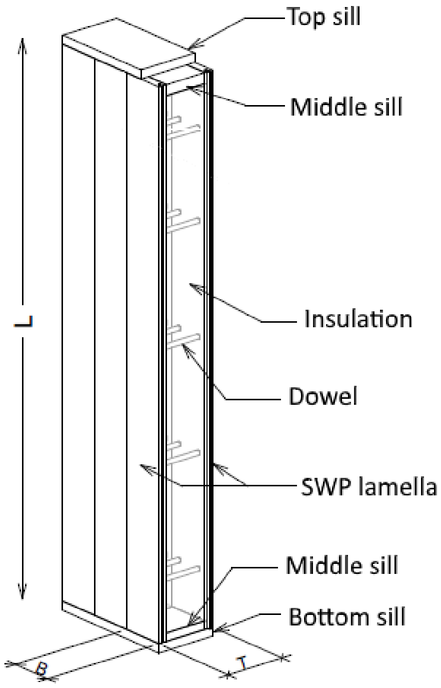


Figure 3-5: Construction details of Termowood wall. Source:Termowood (2017)

The middle sill is located between the SWP panels of the TW element in the top and bottom of the wall-length. For the experiment, it is tested two different materials in the middle sill. The first is a structural timber and the second is a SWP material. The SWP product used in the tests is retrieved from the supplier Binderholz GmbH in Austria.

The top/bottom- and the middle-sill were fastened together with two diamond coated nails. During testing, it was decided that an extra screw should be mounted in the middle of those sills, to reduce any disunity between them. The top/bottom sill henceforth be referred to as the bottom sill only. Below follows a detailed description of both middle sill material.

Structural Timber

The geometry for the middle sill with structural timber is 48x120x300mm with strength class C24, henceforth referred to as timber C24 sill (figure 3-6). Table 3-4 presents characteristic properties for structural timber C24.

Figure 3-6: Bottom sill connected to a middle sill of structural timber C24.

Table 3-4: Characteristic properties for structural timber C24. Source: NS-EN 338:2016 table 1

Property			
Bending	$f_{m,k}$	24	N/mm^2
Tension parallel to the grain	$f_{t,0,k}$	14,5	N/mm^2
Tension perpendicular to the grain	$f_{t,90,k}$	0,4	N/mm^2
Compression parallel to the grain	$f_{c,0,k}$	21	N/mm^2
Compression perpendicular to the grain	$f_{c,90,k}$	2,5	N/mm^2
Shear	$f_{v,k}$	4,0	N/mm^2
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	11000	N/mm^2
Mean shear modulus	G_{mean}	690	N/mm^2
Density 5 percentile	ρ_k	350	Kg/m^3
Mean density	ρ_{mean}	400	Kg/m^3

SWP

The geometry of the middle sill with SWP material is 40x120x300mm (figure 3-7). The reason for testing SWP sill in this fashion, is due to the producers assembling and recommending their product this way to their customers. We wanted to evaluate this specific use of the product compared to the structural timber, which is more common. The orientation of the SWP material brought up some questions about the minimum distances of the fasteners, from the TW element to the middle sill. Table 3-5 presents the characteristic properties for SWP material.

Figure 3-7: Bottom sill connected to a middle sill of SWP material.

Table 3-5: Characteristic properties for SWP material from supplier Binderholz GmbH. Source: Binderholz (2018)

Property			
Nominal Thickness		40,00	*mm*
Top Layers		8,45	*mm*
Central Layer		23,10	*mm*
Bending parallel to the grain	$f_{m,0}$	24,4	N/mm^2
Bending perpendicular to the grain	$f_{m,90}$	11,4	N/mm^2
Modulus of elasticity parallel bending	$E_{m,0}$	9700	N/mm^2
Modulus of elasticity perpendicular bending	$E_{m,90}$	2600	N/mm^2
Shear modulus	G	60	N/mm^2

Unfortunately, the density of the SWP material was not available from the manufacturers webpage (i.e. Binderholz GmbH), however according to NS-EN 13353 (2008 - table 4) the density for a multi-layered solid wood panel with nominal thickness between 12 and 42 is given as 410 kg/m^3. This value can then be used for calculating the estimated maximum load, F_{est}, when evaluating this material.

3.2 Experimental Investigation

In this chapter, the experiments are presented. All the experiments are tested at the laboratory for timber materials, and the customized steel design used to set up the experiment where made at the laboratory for steel materials. Both are located at Norwegian University of Life Sciences (NMBU). The machine used for the laboratory tests is an INSTRON 5800, which continuously record load and slip values. Furthermore, local measuring instruments were used on the specimen during testing to confirm and correct deformations at the focus area.

The experiment has three different studies, henceforth referred to as study 1, study 2 and study 3. The studies will be described in more details below.

3.2.1 Configuration of the Experiment

The purpose of study 1 and study 2 is to investigate the sill-connectors and will therefore have some common configurations. The forces of interest in these studies are the horizontal and the vertical forces affecting the element. Study 1 addresses the horizontal force and study 2 addresses the vertical force. Lastly, study 3 investigates the vertical tongue and groove connection between each TW element. Figure 3-8 below shows a description of the studies main focus on a shear wall with forces acted upon it.

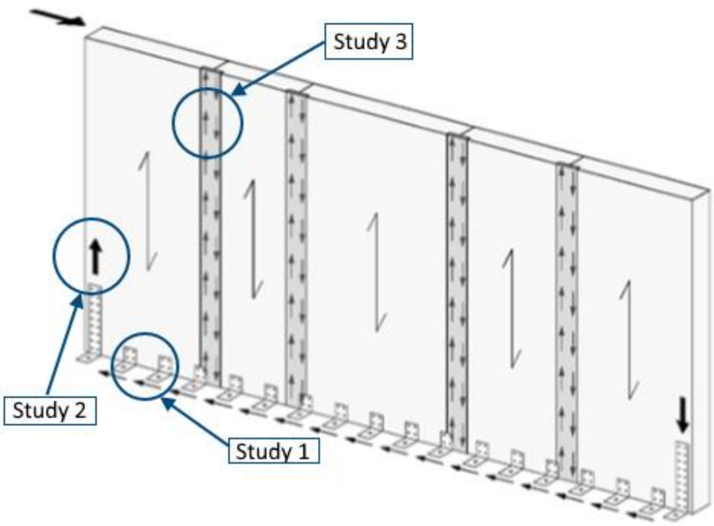


Figure 3-8: Force distribution on CLT shear wall with connectors. Source Roberto Tomasi lecture TBA390 slide 5.

Firstly study 1 and 2 investigates the sill connectors. The test configuration for the studies are divided into three main characters (i.e. connector type, connector angle, and middle sill material). The connector types are screws and nails, which are divided by orientation (i.e. horizontal (90°) and angular (60°) angle) and each angle is divided into two different sill materials (i.e. SWP and timber C24). The angle degree is the angle between the connector and the grain of the external layer of the TW panel. Figure 3-9 visualizes the connectors angle.

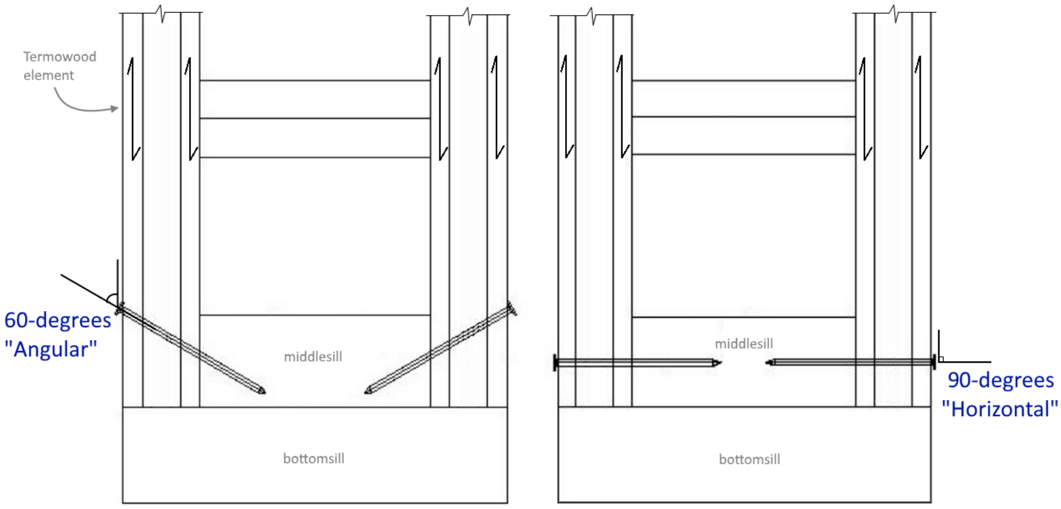


Figure 3-9: Representation of the connectors angle configurations, 60-degrees and 90-degrees respectively.

These configurations henceforth called test groups. Each study consist of eight test groups, where each group have five (study 1) to eight (study 2) similar specimens tested to ensure reliability of the results. Table 3-6 gives an overview of the explained configurations.

Table 3-6: Overview of nail and screw configuration for study 1 and 2.

Screw Configuration			
Horizontal (90-degree)		Angular (60-degree)	
SWP sill	Timber sill	SWP sill	Timber sill
Nail Configuration			
Horizontal (90-degree)		Angular (60-degree)	
SWP sill	Timber sill	SWP sill	Timber sill

Study 1 tests for both monotonic load (study 1.1) and cyclic load (study 1.2), resulting in three sill-connector studies (i.e. study 1.1, 1.2 and 2). In sum, there are 24 test groups assembled for the sill-connector study, which translates to 144 specimens.

The labels for each test group in study 1 and 2, is set as acronyms from which configuration they are affiliated with. Table 3-7 gives an explanation of the specimen label.

Table 3-7: Overview of specimen labels in study 1 and 2.

Specimen label: XYZa			
X	Y	Z	a
Orientation	*Connector type*	*Sill material*	*Load type test*
A = Angular 60° to outer panel grain H = Horizontal 90° to outer panel grain	S = Screws 5,0x90mm N = Nails 3,1x90mm	S = SWP material T = Timber C24	s = static/monotonic load test c = cyclic load test

The purpose of the test groups is to investigate how different angles (60 and 90 respectively) and sill materials affect the force resistance of the sill-connectors. The producer assembly-document suggest that it is favourable to assemble the elements with a horizontal (90-degree) sill-connection. However, at building site the product assembly may vary in contrast to a laboratory configuration. Therefore, the choice of an angular orientation is feasible for testing sill-connectors with build-site variation. A larger degree than 60-degree would either require the connector to be positioned high on the TW element or penetrate both middle- and bottom sill. However, the length of the connector did not meet the requirements from NS-EN 1995-1-1 (2004) regarding the connector length when penetrating both middle and bottom sill. Furthermore, a heightened position of the connector does not meet the producers' requirement of concealing the connectors with floor skirting.

For study 3, which aim is to study the vertical connection between TW elements, the study is divided into two test groups. The first being with fasteners (WF) and the second without fasteners (WOF). Each group contains five similar specimens, for reliability.

The assembly of each specimen was done at the timber laboratory at NMBU under supervision from professor Roberto Tomasi and a representative from Termowood AS. The specimens were manually assembled (figure 3-10), which may affect the reliability of the results. A nail gun was used during the assembly, which may contribute to variation in the angle of the nail connectors (figure 3-11). These limitations must be considered when analysing the results. However, the variation during the assembly may reflect real-life assembly on-site, which is further discussed in chapter 5.6 *Implications and limitations.*

Figure 3-10: Attaching the Termowood element to the middle sill with a 60-degree angle screw connector.

Figure 3-11: Attaching Termowood element to middle sill with a 60-degree angled nail connector.

Connections strength capacity

As described earlier for the testing procedure of the Norwegian standards, the estimated maximum force, F_{est}, of the connectors must be calculated before the conduction of the experiment. The values have a key role in the testing protocol for both monotonic and cyclic load tests.

The calculations according to Johansen's theory from NS-EN 1995-1-1 (2004) are with some few moderations, called the modified Johansen model. Since the Termowood product is a SWP material, the product can follow the same guidance as for CLT material. The connectors are positioned perpendicular to the lateral surface of the TW product and the calculations of embedding strength according to the formula proposed by Blaß et al. (2006) is:

$$f_{h,1,k} = 0{,}019 \cdot \rho_{B,k}^{1{,}24} \cdot d^{-0{,}3} \tag{13}$$

Where $\rho_{B,k}$ is the characteristic bulk density of the material in kg/m^3 and d is the nominal diameter of the connector in mm. The density for SWP material is set at 410 kg/m3, as stated earlier. This calculation from Blaß et al. (2006) is used for CLT products with layers of more than 9 mm in thickness. The TW products outer layer are 8,45 mm thick, meaning that the product is below the minimum criteria. However, since the product only deviates with 0,54 mm from the minimum criteria, it was after some discussion decided to accept the use of the calculations.

The embedment strength for the SWP material situated in the middle sill is different than for the equation stated above. This is due to the orientation of the material, which with its endgrain facing the connector, suggest that the connection goes through the edge surface of the element. The embedment strength according to Blaß et al. (2006), is as follows:

$$f_{h,2-swp,k} = \frac{32 \cdot d^{-0,3}}{2,5 \cdot \cos^2 \varepsilon + \sin^2 \varepsilon} \tag{13}$$

Where the $f_{h,2\text{-}swp,k}$ refers to the second SWP element which the connector penetrates, i.e. the middle sill with SWP material. The ε is the angle between the connector and the outer layers grain.

The embedding strength for the middle sill with timber as material, according to NS-EN 1995-1-1 (2004) this is:

$$f_{h,2-timber,k} = 0,082 \cdot \rho_k \cdot d^{-0,3} \tag{14}$$

Where the $f_{h,2\text{-}timber,k}$ refers to the timber C24 middle sill, ρ_k the characteristic density which is set as 350 kg/m^3 and d the diameter of the connector.

The embedment strength for each connector with different elements are represented in table 3-8.

Table 3-8: Overview of embedding strength for each connector.

Connector type	Diameter	Embedment strength		
	d	$f_{h,1,k}$	$f_{h,2\text{-}swp,k}$	$f_{h,2\text{-}timber,k}$
	mm	*N/mm²*	*N/mm²*	*N/mm²*
Screw	5,0	20,37	7,90	17,71
Screw	4,2	21,46	8,32	18,66
Nail	3,1	23,51	9,12	20,44

The characteristic withdrawal resistance for screws is calculated according to the equation derived from Blaß and Uibel (2007), which is:

$$F_{ax,Rk} = \frac{31 \cdot d^{0,8} \cdot l_{ef}^{0,9}}{1,5 \cdot \cos^2 \varepsilon + \sin^2 \varepsilon} \tag{15}$$

Where l_{ef} is the effective penetration length in millimetres, and d the nominal diameter of the screw. For nails, the calculation method for the withdrawal resistance is divided into two parts, namely horizontal and angular orientations. In addition, according to NS-EN 1995-1-1 (2004), connectors assembled horizontally into the SWP middle sill, gives zero withdrawal resistance due to assemblage into end grain of the material. Also stated in NS-EN 1995-1-1 (2004 - 8.3.2), nails overall incapable of transmitting any axial load when assembled into end grain, results in zero withdrawal resistance too.

Furthermore, two equations for withdrawal resistance in nails, with timber as middle sill, are presented and is divided in the connectors orientation. The equations are taken from NS-EN 1995-1-1 (2004) equation 8.24 (a) and (b). The first equation for horizontal orientation is:

$$F_{ax,Rk} = f_{ax,k} \cdot d \cdot t_{pen}\ (horizontal\ nail) \tag{16}$$

Where t_{pen} is the penetration depth in mm and $f_{ax,k}$ is the nails withdrawal resistance retrieved from the supplier, Motek. For diamond coated nails, the withdrawal resistance is 20% higher than regular nails, giving a resistance of $f_{ax,k}$ = 9,13 N/mm^2. The second equation for nails with angular orientation is:

$$F_{ax,Rk} = f_{head,k} \cdot d_h^2\ (angular\ nail) \tag{17}$$

Where d_h is the nail heads diameter in millimetre and $f_{head,k}$ is the nail heads characteristic penetration resistance, which is retrieved from the supplier, Motek, and is $f_{head,k}$ = 16,88 N/mm^2. The values of the characteristic withdrawal resistance are stated in table 3-9.

Table 3-9: Overview of characteristic withdrawal resistance for screws and nails in varied materials and inclination.

Connector type	Material	Dimensions *mm*	$F_{ax,Rk}$ *N*
Screw (Angular)	SWP	4,2x51	1053,21
	Timber SWP	5,0x90	2762,10
Screw (horizontal)	Timber SWP	5,0x90	3798,49 0,00
Nail (Angular)	Timber SWP	3,1x90	713,80 0,00
Nail (horizontal)	Timber SWP	3,1x90	1415,46 0,00

The calculations for the connectors characteristic load-carrying capacity per shear plane, $F_{v,Rk}$, are values providing the estimated maximum load of the specimen. The capacity is according to the calculations from NS-EN 1995-1-1 (2004 - 8.2.2 a-f) and the values for each connector is presented in table 3-10.

Table 3-10: Characteristic load-carrying capacity per connector per shear plane, in accordance with NS-EN 1995-1-1:2004 – 8.2.2 (8.6).

Connector type	Dimension *mm*	Material	$F_{v,Rk}$ *kN*	Failure mode
Screw	4,2x51	SWP	0,91	(c)
	5,0x90	SWP	0,98	(e)
		Timber	2,41	(f)
Nail	3,1x90	SWP	2,45	(f)
		Timber	1,14	(f)

The following estimated maximum load, F_{est}, is presented for each study further in this chapter.

Procedure for The Monotonic Load Test

Study 1.1, 2 and 3 were performed with monotonic load test. The experiment for monotonic loaded tests are conducted in accordance with the Norwegian Standard NS-ISO 6891 (1991). An explanation on how the standard was applied to the experiment is briefly discussed in the following section. First, the moisture content and standard atmosphere will be described, followed by the estimated maximum load and lastly, how the load procedure was conducted.

The standard conditionings required for the environment is the standard atmosphere 20/65, according to ISO 554. This is strictly followed at the NMBU laboratory, situated in a controlled environment. The materials were stored in this environment for more than four weeks prior to testing, to achieve the right moisture content for the specimen. Moisture content for each specimen was measured right after, or as close as possible after executed test. An FMD hybrid sensor wood moisturemeter with a hammer probe was used to measure the moisture content in the element. Figure 3-12 visualizes how deep the measure pins penetrate the Termowood element, as one can see, the measuring reads moisture in the mid-lamella.

The moisture content in each represented material measured with the oven-drying method, giving an accurate measurement of the material. This is explained in more detail in chapter 3.3 *Moisture Content.* Values from the moisture content measurements can be found for each study in the appendix.

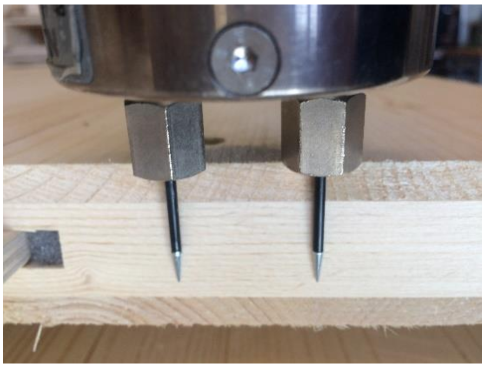


Figure 3-12: Closeup photo of the hammer probe used for the FMD hybrid sensor wood moisturemeter, showing the depth of the pins into the Termowood element.

An estimated maximum load, F_{est}, must be calculated before the experiment and adjusted afterward if necessary, according to NS-ISO 6981 (1991). Adjustments are allowed if the mean value of the maximum load deviates by more than 20 % of the estimated maximum load. It is then allowed to adjust the F_{est} to be the mean value of the maximum load. Each test group is calculated and given a F_{est}, which is presented in tables in the following chapters for each study.

According to NS-ISO 6891 (1991), the rate of load for the tests should correspond to $0,2 \cdot F_{est}$ per minute ± 25 %, and is adjusted in order for the ultimate load or a deformation of 15 mm to be reached after three to five minutes. The values of the load rate and estimated maximum load are presented for each study later in current chapter.

Procedure for The Cyclic Load Test

Study 1.2 was the only study tested for both monotonic and cyclic load test. As for study 2, the cyclic load test was not conducted due to the configuration of the specimen. Study 3 originally included a cyclic load test, which did not materialize because of software-related issues.

The load rate used for study 1.2 were set at 0,2 mm/sec, as stated in NS-EN 12512 (2002) – 6.4.1. The cycle procedure described earlier in chapter 2.2 *Norwegian and European Standards,* states that each cycle amplitude is a specific percentage of the yield slip, V_y, calculated from earlier monotonic load tests. The yield slip determining the cycles amplitude for each test group are presented in table 3-11.

Table 3-11: Cycle amplitudes for cyclic load test.

V_y = 2,00 mm	Displacement
0,25V_y	0,50
0,50V_y	1,00
0,75V_y	1,50
1,00V_y	2,00
2,00V_y	4,00
4,00V_y	8,00
6,00V_y	12,00
8,00V_y	16,00
10,00V_y	20,00
12,00V_y	24,00
14,00V_y	28,00
16,00V_y*	32,00

** 16,00V_y were terminated midway due to restriction of 30 mm slip from NS-EN 12512 (2002)*

3.2.2 Study 1

The purpose of study 1 is to investigate the horizontal force on a shear wall and how it affects the connectors between the TW element and the middle sill. The study tests for both monotonic (study 1.1) and cyclic load (study 1.2), where it is designed a special steel set-up for study 1.2 to be used in the Instron machine. The geometry and production of the specimen is discussed, followed by the Instron steel design set-up and relevant software applied.

Geometry and Production

The layout is set up with two sill elements on each side, consisting of a bottom and middle sill, with the TW element in between. The load is positioned in the middle of the specimen and corresponds to a compressive load in the monotonic test, and both compressive and tension load in the cyclic test. The geometry for study 1 is shown in figure 3-13.

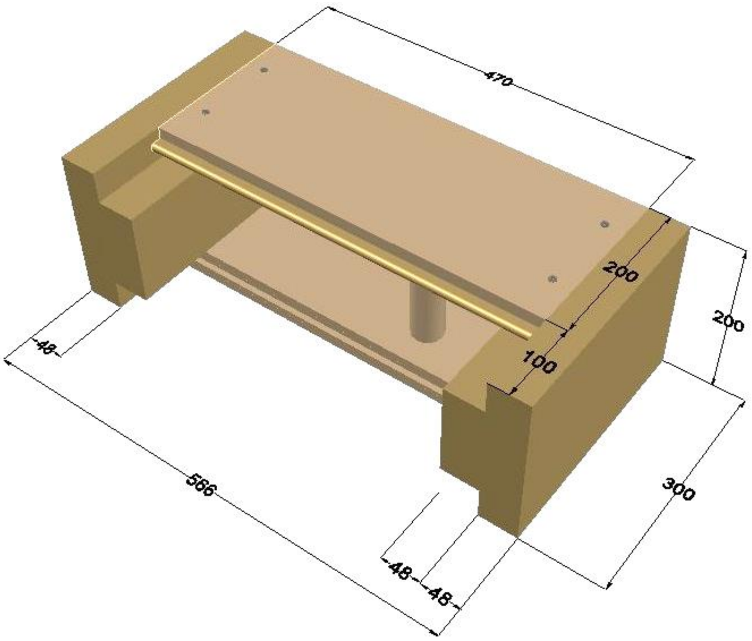


Figure 3-13: Study 1 specimen layout.

Two fasteners connect the TW element with the middle sill on each side, resulting in eight connectors for a test specimen. Table 3-12 and table 3-13 provides an overview of the test configurations for study 1.1 and study 1.2, respectively.

Table 3-12: Study 1.1 test configuration.

		Angle	*Sill*	*n°*
Study 1.1 Monotonic load test	Screw	90-degree	Timber C24	5
			SWP	5
		60-degrees	Timber C24	5
			SWP	5
	Nail	90-degree	Timber C24	5
			SWP	5
		60-degree	Timber C24	5
			SWP	5
Σ				40

Table 3-13: Study 1.2 test configuration.

		Angle	*Sill*	*n°*
Study 1.2 Cyclic load test	Screw	90-degree	Timber C24	5
			SWP	5
		60-degrees	Timber C24	5
			SWP	5
	Nail	90-degree	Timber C24	5
			SWP	5
		60-degree	Timber C24	5
			SWP	5
Σ				40

Minimum distances

Minimum and chosen distances for the connectors in study 1.1 and 1.2 are presented in table 3-14 and table 3-15. The length of penetration for both screw and nail in angular position is t_{pen} = 40 mm and t_{pen} = 50 mm for horizontal position. The minimum distances are retrieved from Uibel and Blaß (2013) and NS-EN 1995-1-1 (2004).

Table 3-14: Minimum and chosen distances for screw connections in study 1.1 and study 1.2. (Uibel and Blaß, 2013)

Screw orientation		a_2 *mm*	$a_{4,c}$ *mm*	$a_{4,t}$ *mm*
Horizontal, 90 degrees	Minimum distances	> 12,5 2,5·d	> 12,5 2,5·d	> 30 6·d
Horizontal, 90 degrees	Chosen distances	100	50	50
Angular, 60 degrees	Minimum distances	> 12,5 2,5·d	> 12,5 2,5·d	> 30 6·d
Angular, 60 degrees	Chosen distances	100	50	50

Table 3-15: Minimum and chosen distances for nail connections in study 1.1 and study 1.2 (Uibel and Blaß, 2013)

Nail orientation		a_2 (mm)	$a_{2,t}$ (mm)	$a_{2,c}$ (mm)
Horizontal, 90 degrees	Minimum distances	> 9,3 3·d	> 22 7·d	> 9,3 3·d
Horizontal, 90 degrees	Chosen distances	100	27,5	50
Angular, 60 degrees	Minimum distances	> 9,3 3·d	> 22 7·d	> 9,3 3·d
Angular, 60 degrees	Chosen distances	100	27,5	50

Test Set-Up

The set-up is designed for the specimen to fit the Instron machine for study 1.1 and 1.2 differs, due to the load acted upon the specimen. It was not necessary to customize an Instron steel set-up for study 1.1 (monotonic load), since the load test was only a compression force and the layout of the specimen did not risk buckling in an unfavourable way. However, it was necessary to design a clamping system for study 1.2

(cyclic load) that would maintain the specimen on the baseplate of the machine, during the tension forces pulling it upwards. The customized steel clamping system was produced by engineers at the laboratory for steel materials at NMBU. The specimen for study 1.1 is shown in figure 3-14 and the steel clamping system and study 1.2 can be viewed in figure 3-15 and figure 3-16.

Figure 3-14: Study 1.1 monotonic load test specimen ready for testing in the Instron machine.

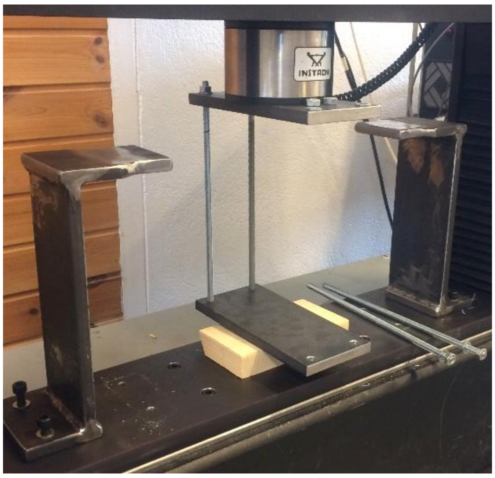


Figure 3-15: Study 1.2 clamping system and Instron test set-up.

Figure 3-16: Study 1.2 cyclic load test specimen during testing in the Instron machine.

For study 1.2 is the Instron cell located in the middle of the specimen and are connected to the TW element through steel plates and bars. The system locks the Instron cell around the TW element, moving the element with the machine under compression and tension load. The force is distributed to the sill-connectors as shear load.

Local measurement instruments were used during testing, its purpose is to give a local displacement measure on the sill-connectors during the test. This is due to the Instron steel set-up that contaminate the global displacement measurements in the Instron cell. Unfortunately, were the instruments not accessible during the early stages of the experiment, resulting in a lack of local measurements in study 1.1. In addition, were some of the instruments reading bars not long enough to be used in study 1.2, resulting in only one instrument reading the local displacement from one sill.

Instron software

Bluehill 2 and LabView are the software programmes used for the Instron machine. Bluehill 2 is an advanced software that enables to programme the preload stage, as well as cycled loads, whereas LabView does not provide that. Due to restriction in obtaining Bluehill 2 in the beginning, LabView were used in study 1.1 for the Instron machine. Because of the simplicity of LabView, the preload cycle in study 1.1 were performed manually using the stop button while watching the load continuously. This procedure does not save the preload cycle, meaning that the main load-to-breakage stage is the only thing that is recorded. From study 1.2 and onwards, Bluehill 2 was used, while LabView was only applied to read the local measuring instruments.

For study 1.1 the load rate was set as 2 mm/min in the beginning. After the first test, the load rate was adjusted to 4 mm/min to adhere to the correct testing time based on NS-EN 6891 (1991). Further into testing of study 1.1, the load rate was adjusted once more after F_{est} and became 5,8 mm/min.

For study 1.2 (cyclic load) a yield slip, $V_{y,est}$, had to be calculated. The value was retrieved from study 1.1. As explained earlier, study 1.1 lacks data from the preload stage due to restriction of software program, Bluehill 2. This means that the yield slip calculations stated from NS-ISO 6891 (1991) is not possible to obtain. It was then necessary to use other methods, such as the yield slip calculations from NS-EN 12512(2002), which turned out to be a very challenging calculation to program. The solution was then to use Yasumura and Kawai’s yield slip proposal, also called 10-40-90 principle. Later on, after the experimental phase, the yield slip procedure from NS-EN 12512(2002) was calculated for study 1.1.

After calculating the yield slip from study 1.1, it was decided to set the estimated yield slip, $V_{y,est}$, at two millimetres for all the specimens in study 1.2. It was foreseen that the global displacement measuring from the Instron machine would not be as accurate as desired, due to all the steel set-up that would contaminate. It was then included an extra 1 mm to $V_{y,est}$. There was a time-restriction argument, ensuring that each test did not last more than two hours, resulting in the value of two millimetres.

The load rate for all the tests was 12 mm/min = 0,2 mm/sec, which is the maximum rate, according to NS-EN 12512 (2002). Twelve cycle blocks were designed in Bluehill 2 and a criterion defined to stop at 30 mm displacement. Each test took up to two hours to conduct. Table 3-16 describes the estimated maximum load and load rate for study 1.1 (the adjustments that were made are written in brackets).

Table 3-16: Estimated maximum load and load rate for study 1.1 (adjustments are written in brackets).

	study 1.1	
	F_{est}	main-load rate (preload rate is the same)
	kN	*mm/min*
ANSs	14	5,8
ANTs	14	5,8
ASSs	20	4
ASTs	20	2 (4)
HNSs	14	5,8
HNTs	14	5,8
HSSs	20	4
HSTs	20 (29)	4 (5,8)

3.2.3 Study 2

Study 2 is the experiment investigating the vertical force on a shear wall. The study focuses on sill-connectors between the TW element and the middle sill but does not contain a cyclic load test as in study 1. In this chapter, the geometry and production of the specimen is presented, as well as the steel clamping system for the Instron machine and relevant software applied.

Geometry and Production

The layout for study 2 is similar to study 1, with the only difference being one less sill in study 2. The study is carried out with a tension force that is pulling on the TW element, corresponding to shear load and withdrawal force on the sill-connectors. The geometry for study 2 is shown in figure 3-17.

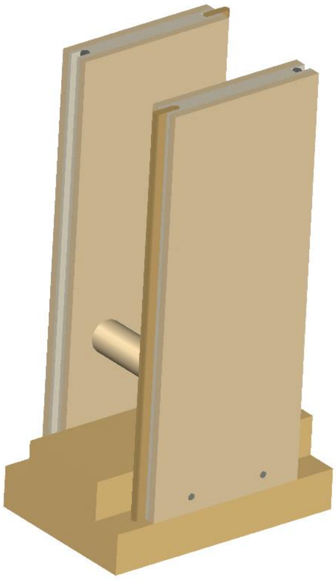


Figure 3-17: Study 2 specimen layout.

There is in total four sill-connectors in a specimen. The test configuration is the same as for study 1, except for the number of specimen per group where study 2 has eight specimens instead of five. The reason is merely availability of more elements. An overview of the configuration is presented in the table 3-17.

Table 3-17: Study 2 test configuration.

		Angle	*Sill*	*n°*
Study 2 Monotonic load test	Screw	90-degree	Timber C24	8
			SWP	8
		60-degrees	Timber C24	8
			SWP	8
	Nail	90-degree	Timber C24	8
			SWP	8
		60-degree	Timber C24	8
			SWP	8
Σ				64

The assembly of study 2 was conducted at the same time as study 1. The resolution for the connectors angle and sill materials are the same as for study 1, stated earlier in this chapter.

Minimum Distances

The minimum and chosen distances for the connectors is presented in this chapter. The results of chosen distances are similar to study 1, which minimizes the risk of incorrect assembling. Some chosen lengths do not satisfy minimum distances but is chosen due to the authenticity of the product. Table 3-18 and table 3-19 divides the minimum distance values in type of sill material, since the SWP sills are eight millimetres smaller than the timber sill (i.e. height). The penetration length for the connectors is the same as study 1, for angular and horizontal sill-connector respectively is t_{pen} = 40 mm and t_{pen} = 50 mm.

Table 3-18: Minimum and chosen distances for screw connections in Study 2.(Uibel and Blaß, 2013)

Screw orientation	Sill material	Distances	a_2 *mm*	$a_{3,c}$ *mm*	$a_{4,c}$ *mm*	$a_{4,t}$/ $a_{2,CG}$ *mm*
60-degrees	SWP/C24	Minimum	> 12,5 *2,5·d*	> 50 *10·d*	> 20 *4·d*	> 30/20 *6·d/4·d*
60-degrees	SWP/C24	Chosen	100	50	23/31	17
90-degrees	SWP/C24	Minimum	> 12,5 *2,5·d*	> 30 *6·d*	> 12,5 *2,5·d*	> 30 *6·d*
90-degrees	SWP/C24	Chosen	100	27,5	12,5/20,5	27,5

Table 3-19: Minimum and chosen distances for nail connections in study 2. (Uibel and Blaß, 2013)

Screw orientation	Sill material	Distances	a_2 *mm*	$a_{3,c}$ *mm*	$a_{4,c}$ *mm*	$a_{4,t}$ *mm*
60-degrees	SWP/C24	Minimum	> 9,3 *3·d*	> 18,6 *6·d*	> 9,3 *3·d*	> 35 *7·d*
60-degrees	SWP/C24	Chosen	100	50	23/31	17
90-degrees	SWP/C24	Minimum	> 9,3 *3·d*	> 18,6 *6·d*	> 9,3 *3·d*	> 35 *7·d*
90-degrees	SWP/C24	Chosen	100	27,5	12,5/20,5	27,5

Test Set-Up

A customized steel set-up for the Instron machine kept specimens on the baseplate of the machine during the tension forces which pulled upwards. The clamping system fastened to the Instron baseplate was based on the same idea from study 1.2. The clamps are smaller than those in study 1.2, since it only needs to clamp down on the edges of the sill. As a result, less contamination in the displacement measurements is given. Furthermore, a design allowing the Instron cell to attach to the TW element and pull it upwards was created. By drilling a hole through the TW element, a tube with connections up to the Instron cell was constructed. Compression force parallel to the grain were calculated to find a suitable tube diameter that maintained the strength in the

TW panel, decreasing the risk of pressure deformations in the wood that could contaminate the deformation measuring in the Instron cell. The resulting tube diameter was 35 mm. All the steel products were constructed by engineers in the steel laboratory at NMBU. Figure 3-18 and figure 3-19 visualizes a specimen during testing and a close-up of the Instron cell attachment.

Figure 3-18: Study 2 specimen ready for testing in the Instron machine.

Figure 3-19: Study 2 Instron cell tube-connection set-up.

Two local measuring instruments were used during the tests, positioned on each side of the TW element.

Software

Bluehill 2 is the software programme used to control the Instron machine, as described in study 1. LabView is the programme that controls the displacement measuring instruments.

In Bluehill 2, the load rate is divided in two rates. First, the rate at the preload stage, which is set as a force-controlled rate with units kN/min. Second, the rate at the main-load stage, which is set as a displacement-controlled rate with units mm/min. This rate division is different from study 1.1 and was operated due to the access of the software programme Bluehill 2, which allows to divide the load rate in two divisions, making the preload stage follow the standard protocol more precise. The preload rate is set as 0,4·Fest so that this stage only takes three minutes to be performed. Afterwards, it was figured out that this preload rate was wrong from the standards protocol. In the standard protocol it is stated 0,2·Fest, meaning that the preload stage for this experiment was conducted too fast.

The main-load rate is the same for all specimen and was set at 2 mm/min in the beginning but were adjusted to 1,5 mm/min due to the testing time.

In each group, an estimated maximum force, F_{est}, is calculated. When the first maximum value, F_{max}, is retrieved after testing in a group and the value deviates by 20 % from F_{est}, it will be adjusted according to guidelines in NS-EN 6891 (1991). The overview of each test groups F_{est} and load rate is presented in table 3-20.

Table 3-20: Estimated maximum load and load rate for study 2 (adjustments during test is presented in brackets).

	study 2		
	F_{est}	Preload load rate	main-load rate
	kN	*kN/min*	*mm/min*
ANSs	3 (6)	1,2 (2,4)	1,5
ANTs	4 (5)	1,6 (2)	1,5
ASSs	6,25 (11)	2,5	1,5
ASTs	8,62 (13)	3,5 (5,2)	1,5
HNSs	3 (5)	1,2 (2)	1,5
HNTs	5	2	1,5
HSSs	3,93	1,6	2 (1,5)
HSTs	3,93 (11)	4,4	1,5

3.2.4 Study 3

The purpose of Study 3 is to investigate the vertical tongue and groove connection between TW elements. Each specimen was tested for in-plane shear forces with and without fasteners in the vertical connection. The tests without fasteners investigated the friction between the tongue and groove in TW element and the tests with fasteners evaluates the strength of the vertical joint when fasteners are applied. A monotonic and cyclic load test were planned to be performed, but unfortunately only monotonic load test was executed due to lack of Instron set-up and software programmes. The assembly of study 3 was conducted by the employees at Termowood headquarter in Hurdal. The geometry and production of the specimen is presented, as well as the Instron steel set-up and relevant software applied.

Geometry and Production

The layout is build up by three, one metre long TW elements connected to each other with the vertical tongue and groove. The element in the middle is placed 100 mm higher than the other elements and two small timber beams are positioned through the elements at the top and bottom, fastened only to the two outer TW panels. The timber beams contribute to the normal force acting perpendicular on the tongue and groove system, giving a higher friction, which increases the shear force resistance. This reflects real-life assembly with the middle sill, as well simplified moving the specimen around the laboratory, without disturbing the vertical connection (i.e. study without fasteners). The geometry of the specimen is shown in figure 3-20.

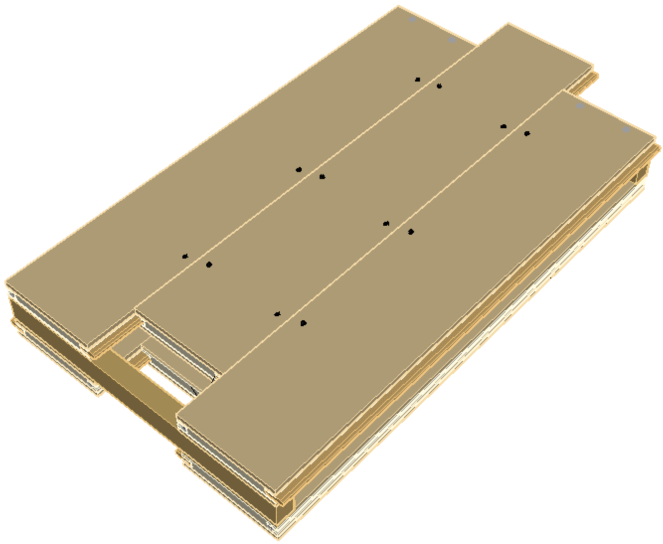


Figure 3-20: Layout for specimen of Study 3.

There are five specimens for each group, namely with fasteners (WF) and without fasteners (WOF), resulting in a total of ten tests carried out. An overview of the configurations is presented in the table 3-21.

Table 3-21: Study 3 test configuration.

	Angle	*Sill*	*n°*
Study 3 Monotonic load test	45-degree	With fasteners (WF)	5
		Without fasteners (WOF)	5
Σ			10

The force is positioned on the element in the middle, pushing down with a compressive force corresponding to an in-plane shear force on the vertical connection. The test group with fasteners have drilled 4,2x51mm screws with a 45-degree inclination through the vertical joint. There are three connector-set positioned along the vertical joint, where each set is a combination of two screws standing opposite to each other (figure 3-21), in sum six fasteners in each vertical tongue and groove joint. In total, 24 screws for each specimen. It is essential for the producer that the product is aesthetically beautiful for exposed wood, meaning that less visible connectors is favourable. That is why three connector-groups is investigated instead of any higher number. Figure 3-21, shows an example of the layout with minimum distances for the fasteners.

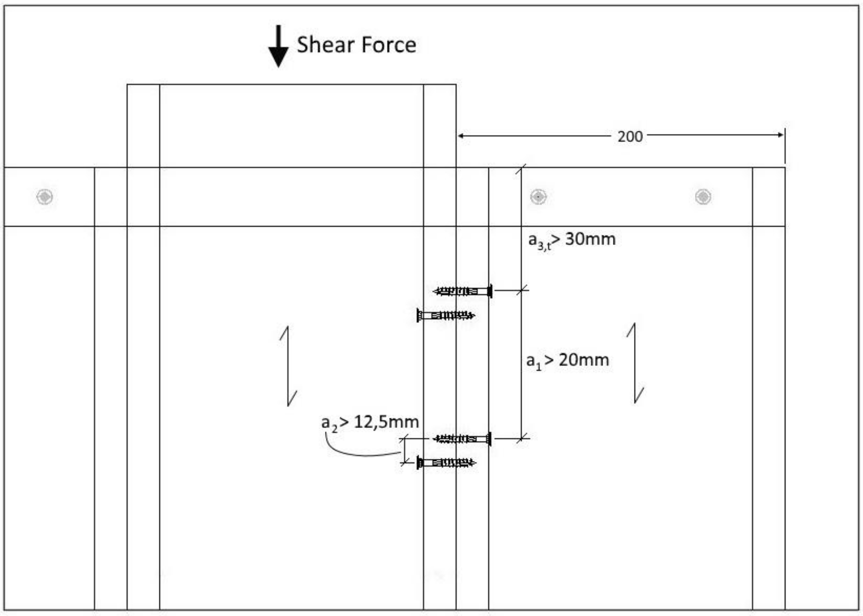


Figure 3-21: Minimum distances for fasteners in vertical tongue and groove connections.

Minimum Distances

The minimum and chosen distances for the connectors in the test group with fasteners are in line with the suggestions from Uibel and Blaß (2013), represented in table 3-22.

Table 3-22: Minimum and chosen distances for the fasteners in the vertical joint in study 3.(Uibel and Blaß, 2013)

Screw orientation		a_1 *mm*	a_2 *mm*	$a_{3,t}$ *mm*
45 degrees	Minimum distances	> 20 *4·d*	> 12,5 *2,5·d*	> 30 *6·d*
45 degrees	Chosen distances	340	15	100

Test Set-Up

It was not necessary to construct a steel design for the Instron Machine for study 3. The specimen was placed standing on the baseplate, and a steel plate, used from study 1 and 2, were connected to the Instron cell, which pushed down the middle element on the specimen with compressive force. Figure 3-22 shows a specimen with fasteners, ready to be tested.

Figure 3-22: Study 3 specimen with fasteners ready for testing in the Instron machine.

There is no obvious experimental standard to abide by for the test group without fasteners. After discussion with professor Roberto Tomasi, it was decided to run each test with different rates (starting with a low rate), since the friction varies with different parameters. The load-rate is further discussed in the chapter below. It was challenging to determine how much the timber cane increased the friction, so a re-test run was conducted after each test without the timber cane, to evaluate the decrease in friction.

Figure 3-23: : Study 3 specimen without fasteners ready for testing in the Instron machine.

Two local measuring instruments were positioned in the middle on each side of the specimen to monitor the displacement of the middle element.

Software

The tests with fasteners the experiments followed NS-EN 6891 (1991), which includes a preload stage as explained earlier. The preload rate is 0,4·F_{est} with units kN/min, and the main-load rate is set at 1,5 mm/min with endpoint criteria equal to 15 mm. Table 3-23 provides an overview over the calculated estimated maximum load and load rate for study 3 with fasteners (WF).

Table 3-23: Estimated maximum load and load rate for study 3 With Fasteners (WF).

study 3 With Fasteners (WF)			
	F_{est} *kN*	preload rate *kN/min*	Main-load rate *mm/min*
WF	13,42	5,4	1,5

For the tests without fasteners (WOF), it was experimented with different rate controls to observe how the friction were affected. The first test was with displacement-control rate, were the displacement-rate was set at 0,1 mm/min and end-criteria at 10 mm, and the rest was conducted with force-control rate. After the first test, an approximately maximum load at two kilonewtons were retrieved. A force-control rate was then calculated for the other tests by dividing the maximum load with a desired testing time. The desired testing time was ten minutes giving a force-controlled load rate at 0,2 kN/min. Starting with a load-rate at 0,2 kN/min, the next tests were increased to 0,4 kN/min, 0,8 kN/min and lastly 1 kN/min. The endpoint criteria were also set at 10 mm, as for the tests with displacement-control rate. In table 3-24, the load rates for each specimen in the test group without fasteners are presented.

Table 3-24: Load rate for each specimen in test group Without Fasteners (WOF) in study 3.

Study 3 without fasteners (WOF)					
Test rate control	Specimen 1 *mm/min*	Specimen 2 *kN/min*	Specimen 3 *kN/min*	Specimen 4 *kN/min*	Specimen 5 *kN/min*
Displacement	0,1				
Force		0,2	0,4	0,8	1

Note: Bluehill 2

3.3 Moisture content

The moisture content was measured with the oven-drying method before the experiment. Two materials from the TW element, one material from the timber C24, one SWP sill and one timber sill were evaluated. The two materials from TW element were cut off from the element, representing a piece of the product. The SWP sill and timber C24 sill were combined sill products with both bottom and middle-sill connected, containing two nails in the product.

The oven-drying method is considered to be more accurate than the electrical moisturemeter. As explained earlier, all the specimens are measured with electrical moisturemeter after tests, to give a more detailed measurements. In short, the oven-drying measurements assess the robustness of the electrical moisturemeter measurements.

The oven-drying method was conducted on materials after four weeks in a controlled environment, hence weight measuring before drying. After the measurements, the material was placed in an oven for drying over two days. Two days in the oven was considered long enough to meet the constant mass. After drying, the weight was measured once more right after removal from the oven, hence weight measuring after drying. Table 3-25 shows the values from the measurements and the resulting moisture content of each material. The equation for calculating the results is as follows:

$$w(\%) = \frac{m_w - m_0}{m_0} \cdot 100 \tag{18}$$

Where m_w is the specimens weight in grams before drying, and m_0 is the specimens weight in grams in absolute dry condition.

Table 3-25: Measurements of weight before and after drying for each material and their moisture content.

Moisture content measurement					
	SWP TW element n°1	SWP TW element n°2	Timber C24	Timber C24 sill	SWP sill
Before drying (*g*)	260,51	268,68	137,00	1949,66	1819,38
After drying (*g*)	234,00	241,38	118,76	1703,40	1602,46
Moisture content (*%*)	11	11	15	14	14

Adjustments of the axial nail strength and screw strength for moisture deviations does not need to be conducted, if the moisture content lies between 9-15 % (Kucera, 1992, p. 75).

4 RESULTS

In this chapter, mean values for each test groups are presented as results in the tables. Data and graphical representations of all specimens tested are reported in Appendix A – Failure Mode Photo, Appendix B – Study 1.1 (Monotonic Load Test), Appendix C – Study 1.2 (Cyclic Load Test), Appendix D – Study 2 and Appendix E – Study 3.

The chapter is divided into monotonic load test results and cyclic load test results. The results are presented under each calculation methods for different standards. Comparison and further discussion of the results are presented in chapter 5 *Discussion.*

Furthermore, the R script used to calculate the results is added as an attachment. Nevertheless, a part of the R script reported in Appendix F – R Script, where it is verified using an external dataset. The verification is discussed in more detail in chapter 5.6 *Comments on the calculations.*

4.1 Monotonic Load Test Results

4.1.1 NS-ISO 6891 (1991)

Study 1.1 – Monotonic load test

Note, study 1.1 lacks data from preload stage, therefore the calculations for yield slip and slip modulus follows the Yasumura and Kawai procedure. Therefore, we observe yield load corresponding to the yield slip.

Table 4-1 Summary values of Study 1.1 with calculations from NS-ISO 6891(1991). Yield point method from Yasumura & Kawai – mean values and standard deviations in brackets.

	Maximum Load (kN)	Displacement at max load (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
ANSs	14,06 (0,59)	13,6 (2,17)	6,63 (0,30)	1,18 (0,23)	5,76 (1,03)
ANTs	11,72 (0,60)	15,0 (0,02)	6,05 (0,46)	1,17 (0,27)	5,32 (0,83)
ASSs	26,65 (1,63)	15,0 (0,01)	11,16 (0,85)	2,24 (0,29)	5,00 (0,27)
ASTs	24,39 (1,55)	14,9 (0,22)	10,38 (1,02)	2,08 (0,94)	5,52 (1,44)
HNSs	11,01 (0,70)	15,0 (0,01)	5,92 (0,46)	0,88 (0,21)	6,93 (1,21)
HNTs	11,40 (0,80)	15,0 (0,00)	6,46 (0,32)	1,24 (0,23)	5,31 (0,83)
HSSs	19,79 (1,21)	14,8 (0,28)	9,83 (1,05)	1,29 (0,30)	7,77 (1,00)
HSTs	26,32 (1,91)	14,2 (1,79)	13,03 (0,47)	1,82 (0,44)	7,45 (1,58)

Study 2

The preload stage was recorded, which means that the calculations for yield slip at slip modulus follows the NS-ISO 6891 (1991) and therefore no yield load calculations is reported. The same applies to study 3.

Table 4-2. Summary values of Study 1.1 with calculations from NS-ISO 6891(1991). Yield point method is the iso-standard – mean values and standard deviations in brackets.

	Maximum Load (kN)	Displacement at max load (mm)	Yield slip (mm)	Slip modulus (kN/mm)
ANSs	5,72 (0,44)	5,37 (2,54)	0,33 (0,12)	7,24 (5,90)
ANTs	4,56 (0,56)	4,70 (2,06)	0,28 (0,07)	4,81 (0,87)
ASSs	12,40 (1,23)	6,75 (2,55)	0,72 (0,18)	7,12 (2,65)
ASTs	13,15 (1,08)	7,01 (2,56)	0,71 (0,16)	7,05 (3,62)
HNSs	5,50 (0,46)	9,25 (1,52)	0,39 (0,05)	4,53 (2,53)
HNTs	5,67 (0,40)	12,56 (2,31)	0,58 (0,09)	2,90 (0,85)
HSSs	7,77 (0,71)	6.05 (1.46)	0,40 (0,06)	13,83 (4,49)
HSTs	11,46 (0,47)	13,03 (1,65)	0,92 (0,21)	21,18 (21,37)

Study 3

The preload stage was not executed on test group WOF. The preload procedure was not necessary, since the specimen have no connectors. The yield point method used in test group WOF calculated from NS-ISO 6891 (1991) follows the Yasumura & Kawai procedure. For the test group WF, the yield point method follows the ISO-procedure stated in NS-ISO 6891 (1991).

Table 4-3. Summary values Study 3 with calculations from NS-ISO 6891(1991). – mean values and standard deviations in brackets. Note that for the WOF test, the load rate varied for the different specimens, and that the individual data in Appendix E – Study 3 may therefore give a better representation of the results.

	Maximum Load (kN)	Displacement at max load (mm)	Yield slip (mm)	Slip modulus (N/mm)
WFs	25,70 (2,33)	7,31 (1,02)	0,51 (0,09)	19,69 (12,33)
WOFs	2,93 (0,88)	7,24 (6,58)	1,77 (0,98)	2,08 (1,41)

4.1.2 NS-EN 12512 (2002)

NS-EN 12512 (2002) is the standard for cyclic load test, but states that the definitions for yield load/slip, ultimate load/slip and slip modulus may be used for monotonic load slip curves. Below are the results for the calculations of monotonic load-displacement curves.

Study 1.1

Table 4-4: Summary values of Study 1.1 with calculations from NS-EN 12512 (2002). Yield point method is the 1/6 procedure – mean values and standard deviations in brackets.

	Maximum Load (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANSs	14,43 (0,91)	13,75 (1,02)	30,0 (0,00)	8,00 (0,86)	1,21 (0,34)	6,85 (1,32)	26,26 (7,55)
ANTs	11,89 (0,59)	10,03 (0,65)	30,0 (0,00)	6,32 (0,48)	1,08 (0,18)	5,90 (0,56)	28,17 (3,93)
ASSs	27,72 (2,08)	22,78 (2,80)	28,4 (1,72)	19,83 (2,22)	4,45 (0,76)	4,49 (0,25)	6,49 (0,85)
ASTs	25,24 (2,10)	21,84 (2,76)	28,2 (2,95)	16,09 (2,45)	3,31 (1,01)	5,09 (1,02)	9,08 (2,50)
HNSs	11,93 (0,67)	11,70 (0,77)	28,2 (4,08)	5,76 (0,22)	0,69 (0,15)	8,62 (1,61)	42,37 (11,39)
HNTs	12,54 (0,71)	12,16 (0,68)	29,5 (1,15)	6,51 (0,29)	1,00 (0,19)	6,65 (1,15)	30,13 (5,32)
HSSs	21,09 (1,39)	20,99 (1,39)	30,0 (0,00)	9,88 (1,14)	0,96 (0,14)	10,35 (0,73)	31,80 (4,69)
HSTs	29,31 (2,84)	28,10 (3,21)	26,2 (8,51)	14,46 (2,34)	1,84 (1,13)	9,36 (3,20)	16,57 (7,59)

Study 2

Table 4-5: Summary values of Study 2 with calculations from NS-EN 12512 (2002). Yield point method is the 1/6 procedure – mean values and standard deviations in brackets.

	Maximum Load (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANSs	5,72 (0,44)	5,01 (0,59)	10,2 (4,99)	4,61 (0,45)	1,11 (0,35)	4,71 (2,42)	10,30 (5,45)
ANTs	4,56 (0,56)	3,72 (0,46)	14,7 (5,75)	3,48 (0,45)	0,94 (0,24)	3,87 (0,92)	17,52 (9,99)
ASSs	12,40 (1,23)	10,21 (1,53)	11,2 (3,10)	9,00 (1,19)	1,84 (0,43)	5,01 (0,79)	6,25 (1,75)
ASTs	13,15 (1,08)	10,52 (0,86)	12,4 (3,64)	10,01 (0,95)	1,90 (0,35)	5,37 (0,68)	6,80 (2,49)
HNSs	5,50 (0,46)	5,02 (0,50)	12,1 (5,14)	2,54 (0,44)	0,89 (0,17)	2,94 (0,63)	14,02 (5,95)
HNTs	5,68 (0,41)	4,78 (0,45)	18,1 (2,78)	2,79 (0,16)	1,29 (0,28)	2,23 (0,35)	14,44 (3,09)
HSSs	8,00 (0,76)	7,49 (0,74)	8,0 (2,79)	4,90 (0,74)	1,80 (1,11)	3,36 (1,37)	5,39 (2,54)
HSTs	11,54 (0,62)	11,01 (0,65)	16,4 (3,10)	6,48 (1,78)	2,61 (1,16)	2,65 (0,62)	7,20 (3,04)

Study 3

Table 4-6: Summary values of Study 3 with calculations from NS-EN 12512 (2002). Yield point method is the 1/6 procedure – mean values and standard deviations in brackets.

	Maximum Load (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
WFs	25,70 (2,33)	18,32 (2,81)	14,7 (5,06)	15,59 (1,43)	1,43 (0,38)	11,39 (2,16)	10,97 (4,82)
WOFs	2,93 (0,88)	2,43 (0,64)	11,5 (4,44)	2,43 (0,75)	0,48 (0,19)	5,17 (0,63)	– –

4.1.3 EN 12512 (2018) Draft Version n°20180410

EN 12512 (2018) proposal provides definitions for calculating ultimate load/slip, yield point and slip modulus on monotonic load-displacement curves and are presented for each study below.

Study 1.1

Table 4-7: Summary values of Study 1.1 with calculations from EN 12512 (2018) Draft proposal. Yield point method is the EEEP curve procedure – mean values and standard deviations in brackets.

	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	ductility
ANSs	14,43 (0,91)	14,43 (0,91)	13,75 (1,02)	30,0 (0,00)	13,29 (0,67)	2,20 (0,47)	5,46 (0,92)	14,09(2,97)
ANTs	11,89 (0,59)	11,89 (0,59)	10,03 (0,65)	30,0 (0,02)	10,75 (0,56)	2,09 (0,25)	4,41 (0,38)	14,49(1,60)
ASSs	27,72 (2,08)	27,72 (2,08)	22,78 (1,72)	28,4 (1,74)	24,21 (2,11)	5,57 (0,80)	3,92 (0,20)	5,16(0,58)
ASTs	25,24 (2,10)	25,24 (2,10)	23,14 (2,33)	28,2 (2,95)	22,04 (1,95)	4,60 (1,07)	4,60 (0,54)	6,32(1,24)
HNSs	11,93 (0,67)	11,93 (0,67)	11,71 (0,77)	28,2 (4,05)	10,34 (0,64)	1,43 (0,28)	6,30 (1,17)	20,35(5,53)
HNTs	12,54 (0,71)	12,54 (0,71)	12,20 (0,71)	29,5 (1,12)	11,09 (0,67)	1,92 (0,25)	5,06 (0,92)	15,56(1,88)
HSSs	21,09 (1,39)	21,09 (1,39)	20,99 (1,39)	30,0 (0,00)	18,70 (1,23)	2,06 (0,22)	8,07 (0,58)	14,71(1,58)
HSTs	29,31 (2,84)	29,02 (3,42)	28,23 (2,94)	26,2 (8,51)	24,45 (3,39)	3,31 (1,49)	7,24 (2,21)	8,37(2,57)

Study 2

Table 4-8: Summary values of Study 2 with calculations from EN 12512 (2018) Draft proposal. Yield point method is the EEEP curve procedure – mean values and standard deviations in brackets.

	Peak Load (kN)	Maximum Load (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANSs	5,72 (0,44)	5,72 (0,44)	4,99 (0,58)	10,20 (4,99)	5,38 (0,40)	1,28 (0,37)	4,54 (1,17)	8,92 (4,88)
ANTs	4,56 (0,56)	4,56 (0,56)	3,72 (0,45)	14,7 (5,75)	4,18 (0,43)	1,10 (0,24)	4,38 (1,60)	14,46 (7,63)
ASSs	12,40 (1,23)	12,40 (1,23)	10,17 (1,49)	11,2 (3,09)	10,99 (0,96)	2,20 (0,52)	5,79 (1,39)	5,17 (1,19)
ASTs	13,15 (1,08)	13,15 (1,08)	10,52 (0,86)	12,4 (3,64)	11,82 (0,99)	2,19 (0,33)	6,01 (0,80)	5,80 (2,00)
HNSs	5,50 (0,46)	5,50 (0,46)	5,02 (0,50)	12,2 (5,13)	4,52 (0,51)	1,37 (0,20)	4,32 (0,91)	8,85 (3,10)
HNTs	5,68 (0,41)	5,68 (0,41)	4,76 (0,43)	18,1 (2,79)	5,01 (0,30)	2,05 (0,39)	3,04 (0,72)	9,00 (1,64)
HSSs	8,00 (0,76)	7,95 (0,79)	7,40 (0,53)	8,0 (2,80)	6,71 (0,74)	2,19 (1,18)	4,72 (0,93)	4,16 (1,65)
HSTs	11,54 (0,62)	11,54 (0,62)	10,89 (0,98)	16,4 (3,05)	9,75 (0,86)	3,80 (1,06)	2,98 (1,34)	4,69 (1,91)

Study 3

Table 4-9: Summary values of Study 3 with calculations from EN 12512 (2018) Draft proposal. Yield point method is the EEEP curve procedure – mean values and standard deviations in brackets.

	Peak Load (kN)	Maximum Load (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
WFs	25,70 (2,33)	25,70 (2,33)	20,56 (1,86)	11,0 (1,75)	22,59 (1,61)	1,84 (0,43)	17,39 (7,01)	6,17 (1,56)
WOFs	2,93 (0,88)	2,93 (0,88)	2,43 (0,64)	11,5 (4,44)	2,78 (0,94)	0,54 (0,22)	6,16 (0,86)	– –

4.2 Cyclic Load Test Results

Cyclic load test results are calculated from both NS-EN 12512 (2002) and EN 12512 (2018). Strength, ultimate load/slip, yield point, slip modulus and ductility values are presented, in addition the equivalent viscous damping ratio and the decrease of strength for each test group, the values are represented as mean values. For more detailed results of each specimen, see Appendix C – Study 1.2 (Cyclic Load Test).

4.2.1 NS-EN 12512 (2002)

Study 1.2

Table 4-10: Results from study 1.2 - cyclic load test, after NS-EN 12512 (2002) Mean values are represented for each test groups and standard deviations are in brackets, positive values for tension and negative values for compression.

Tension/ Compression	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ANSc	9,00/-12,87 (0,78/0,61)	7,21/-10,30 (0,63/0,49)	13,9/-14,1 (0,39/0,82)	6,84 (0,51)	4,0 (1,42)	1,88 (0,59)	3,85 (1,29)
ANTc	8,26/-11,63 (0,48/1,20)	6,61/-9,30 (0,39/0,96)	13,6/-13,5 (0,81/0,22)	5,83 (1,21)	3,9 (2,84)	2,09 (1,05)	5,39 (3,74)
ASSc	19,40/-30,59 (1,52/4,65)	15,52/-24,47 (1,21/3,72)	21,0/-20,4 (1,04/1,27)	15,29 (2,72)	6,4 (2,83)	2,94 (1,63)	4,56 (3,84)
ASTc	17,53/-23,15 (1,54/3,72)	14,02/-18,52 (1,23/2,97)	17,5/-18,7 (1,92/1,63)	14,72 (0,82)	5,5 (0,74)	2,72 (0,42)	3,21 (0,34)
HNSc	8,02/-10,95 (0,53/1,00)	6,41/-8,76 (0,42/0,80)	15,2/-15,1 (0,41/0,84)	4,79 (1,11)	2,8 (2,04)	2,62 (1,83)	9,93 (9,62)
HNTc	8,43/-12,15 (0,79/0,47)	6,74/-9,72 (0,63/0,37)	13,6/-13,6 (0,68/0,39)	7,22 (1,28)	4,7 (1,57)	1,66 (0,47)	3,38 (1,86)
HSSc	15,01/-22,63 (0,63/2,57)	12,01/-18,11 (0,50/2,06)	21,8/-20,9 (1,94/1,76)	11,52 (1,52)	4,5 (1,44)	2,75 (0,88)	5,43 (2,57)
HSTc	17,08/-27,19 (1,39/3,01)	13,66/-21,75 (1,11/2,41)	18,5/-18,9 (1,43/1,10)	12,92 (1,18)	6,0 (2,24)	2,52 (1,33)	3,64 (2,03)

4.2.2 EN 12512 (2018) Draft Version n°20180410

Study 1.2

Below are the results from study 1.2 presented with calculations from the proposal draft EN 12512 (2018) version n°20180410.

Table 4-11: Results for study 1.2 from EN 12512 (2018) Draft version n°20180410 calculations. Mean values are represented for each test groups and standard deviations are in brackets, positive values for tension and negative values for compression.

Tension/ Compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ANSc	9,10/-13,05 (0,76/0,61)	7,91/-11,68 (1,73/0,56)	7,92/-11,68 (1,74/0,56)	9,2/-8,8 (2,91/0,51)	6,50/-9,21 (1,33/0,38)	3,2/-2,2 (0,48/0,69)	1,88/4,10 (0,49/0,88)	2,88/4,21 (0,85/0,88)
ANTc	8,36/-12,16 (0,48/1,22)	7,62/-11,06 (0,77/0,97)	7,58/-11,06 (0,72/0,96)	9,72/-9,16 (0,70/0,43)	6,27/-9,05 (0,88/0,76)	3,62/-2,56 (1,95/1,70)	2,12/6,13 (1,11/6,76)	3,44/6,45 (1,90/6,39)
ASSc	19,94/-30,68 (1,29/4,65)	19,94/-28,72 (1,29/7,67)	18,53/-27,05 (1,92/6,69)	18,0/-15,5 (0,91/4,98)	17,54/-24,32 (1,11/7,46)	6,98/-6,91 (2,29/2,89)	2,58/3,56 (1,16/1,06)	2,96/2,37 (1,49/0,48)
ASTc	17,62/-23,48 (1,53/3,84)	17,54/-22,32 (1,54/3,42)	15,81/-22,30 (1,63/3,45)	15,1/-13,4 (1,41/2,03)	15,22/-17,99 (1,02/2,58)	5,68/-6,03 (0,57/0,67)	2,39/3,00 (0,34/0,17)	2,67/2,24 (0,32/0,33)
HNSc	8,07/-11,02 (0,53/1,00)	8,02/-10,66 (0,56/0,61)	6,99/-9,43 (0,83/1,08)	13,7/-13,1 (1,79/2,41)	6,45/-8,59 (0,43/0,60)	3,29/-2,74 (1,79/0,57)	2,45/3,00 (1,85/0,52)	5,67/5,03 (3,91/1,64)
HNTc	8,56/-12,59 (0,78/0,58)	8,23/-11,95 (0,66/1,19)	8,23/-11,88 (0,66/1,08)	9,7/-9,2 (0,80/0,57)	7,12/-9,85 (0,74/-0,96)	4,32/-2,34 (4,32/-2,34)	1,57/4,81 (0,42/2,72)	2,41/4,89 (0,78/2,76)
HSSc	15,21/-22,85 (0,52/2,60)	14,00/-22,80 (2,58/2,55)	13,28/-21,39 (2,13/-1,98)	16,3/-17,0 (7,17/1,25)	11,87/-19,52 (2,99/1,68)	4,17/-3,74 (2,07/2,01)	3,07/6,09 (1,34/2,49)	4,04/5,54 (1,29/2,56)
HSTc	17,27/-27,72 (1,29/2,75)	17,12/-26,64 (1,22/-2,96)	17,02/-26,20 (1,34/2,84)	15,2/-13,8 (1,46/1,23)	14,98/-21,95 (0,83/2,35)	6,74/-6,20 (2,08/0,77)	2,29/3,59 (1,20/0,61)	2,49/2,27 (0,97/0,44)

4.2.3 Equivalent viscous damping ratio & Decrease of strength

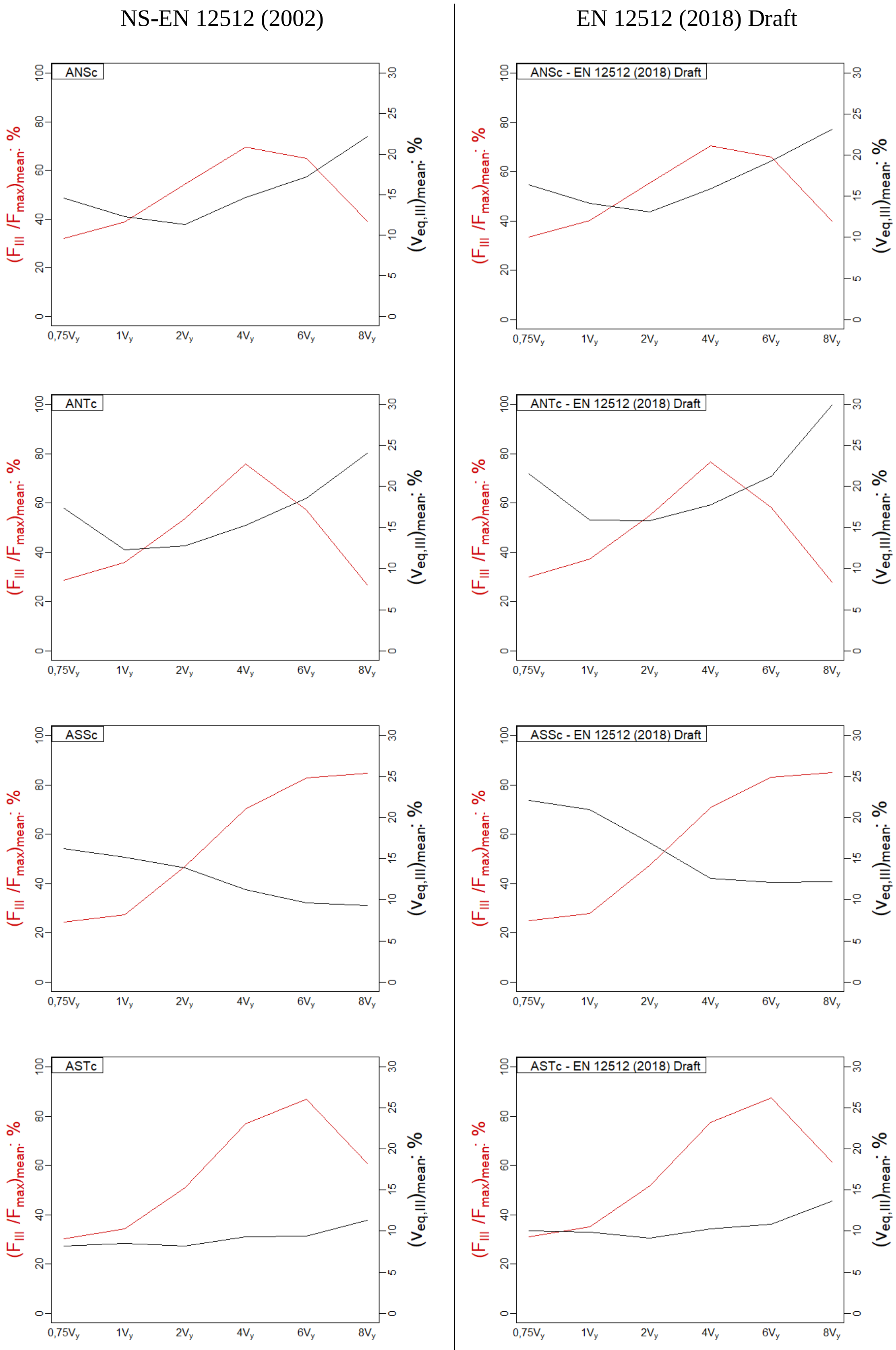


Figure 4-1: Experimental results with mean values. The ratio of the load at the third cycle to the maximum load value reached over the whole test, F_{III}/F_{max} (red lines) and third cycles viscous damping ratio, $v_{eq,III}$ (black lines)

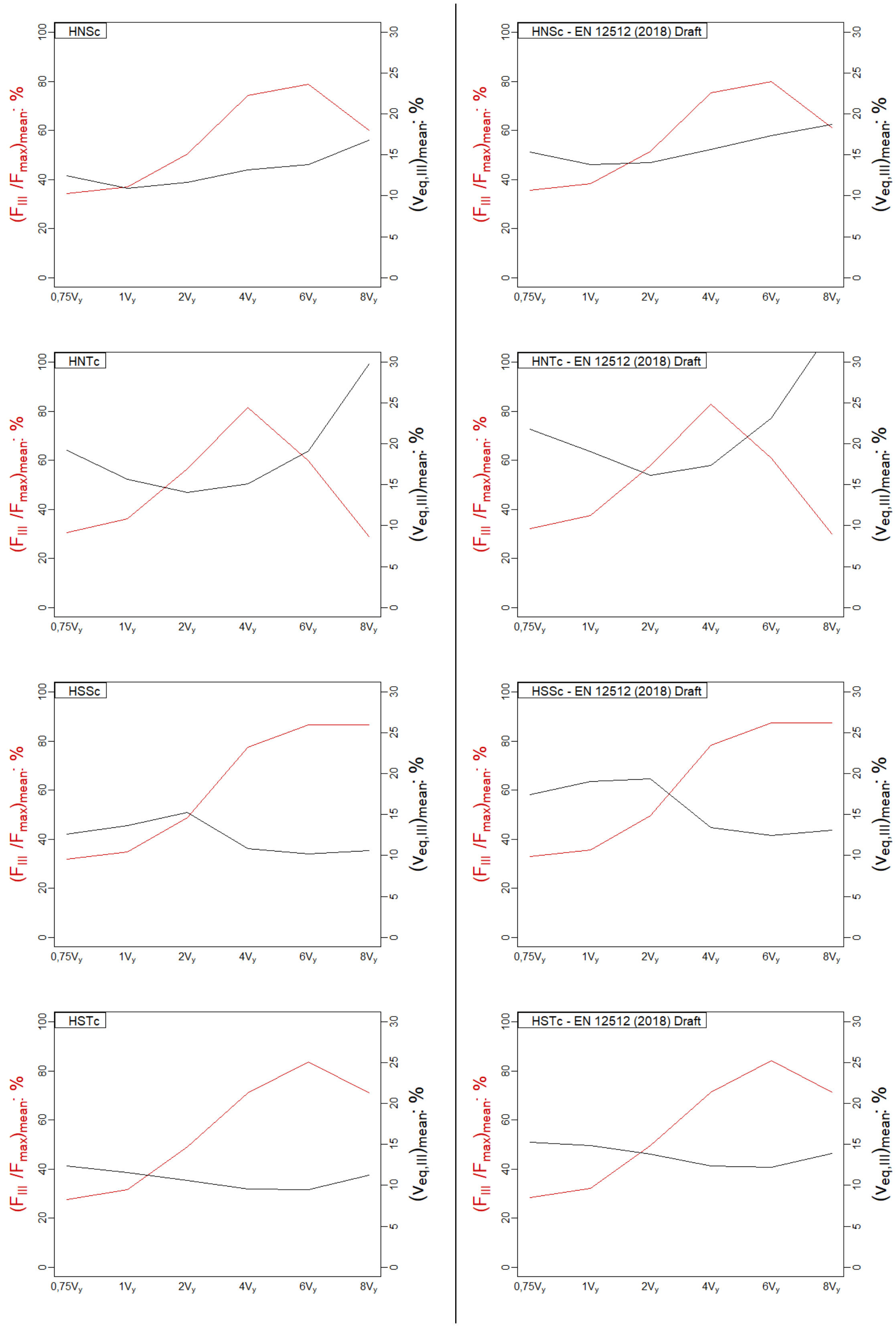


Figure 4-2: Experimental results with mean values for both NS-EN 12512 (2002) and EN 12512 (2002) calculations. Showing the ratio of the load at the third cycle to the maximum load value reached over the whole test, F_{III}/F_{max} (red lines) and the equivalent viscous damping ratio at the third cycle, $v_{eq,III}$ (black lines)

5 DISCUSSION

The chapter is divided into two parts; first, an analysis of the test results from the Termowood products sill connectors and second, a comparison of results conducted from different calculation methods. An explanation of two equations derived and used for the calculations in EN 12512 (2018) is explained. In addition, a discussion on the implications and limitations on this thesis work, and at the end a brief introduction to future research.

The analysis of the Termowood product test results give a brief overview of comparable test groups from study 1 and 2, and recommendation for further research of the sill connection.

Table 5-1 is an overview of yield point method used for each study.

Table 5-1: Overview of yield point methods for each study.

Study	Standard	Yield point method
Study 1.1 (monotonic load test)	NS-ISO 6891 (1991)	Yasumura & Kawai
	NS-EN 1251 (2002)	1/6 procedure
	EN 12512 (2018) Draft	EEEP curve procedure
Study 1.2 (cyclic load test)	NS-EN 12512 (2002)	1/6 procedure
	EN 12512 (2018) Draft	EEEP curve procedure
Study 2	NS-ISO 6891 (1991)	ISO-procedure
	NS-EN 1251 (2002)	1/6 procedure
	EN 12512 (2018) Draft	EEEP curve procedure
Study 3	NS-ISO 6891 (1991)	ISO-procedure
	NS-EN 1251 (2002)	1/6 procedure
	EN 12512 (2018) Draft	EEEP curve procedure

5.1 Analysis of Termowood product

First, a brief comment on the observations of the cyclic load tests failure mode. There was not any obvious failure in the load-displacement curves. However, after every test the specimen were taken apart, which often revealed connection failure in the specimen. The fasteners had either broken in one point or in two, following the Johansen's failure mode (d), (e) or (f) (NS-EN 1995-1-1, 2004 - 8.2.2). In other words, the friction between the TW element and the sills were holding the specimen together with bigger force than expected. Furthermore, specimen from study 1.1 and 2 were taken apart after testing, to observe the connectors failure mode. Photo documentation of this can be found in Appendix A – Failure Mode Photo.

It is important to consider which test groups in study 1 and 2 that are comparable, which the following discussion gives an overview of. It is focused on one chancing parameter for each comparison, to observe differences due to the specific variable, (e.g. SWP material versus timber C24 material). Table 5-2 presents the specimen labels.

Table 5-2: Overview over specimen label explained

Specimen label: XYZa			
X Orientation	Y Connector type	Z Sill material	a Load type test
A = Angular 60° to outer panel grain H = Horizontal 90° to outer panel grain	S = Screws 5,0x90mm N = Nails 3,1x90mm	S = SWP material T = Timber C24	s = static/monotonic load test c = cyclic load test

The results are taken from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations. The compared values are mean values of each test group, and the slip modulus is henceforth referred to as stiffness.

5.1.1 SWP middle sill VS Timber middle sill

In this section, test groups with the same connector and connector angle, but with different middle sill material is compared, to evaluate the effect of the middle sill material.

ASS vs AST

Table 5-3 is a comparison of test groups ASS and AST. The groups have angular connection angles and connector type 5,0x90mm screws.

Table 5-3: Results from ASSs and ASTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
ASS	26,65	5,40	12,40	7,12	19,40/-30,5	2,94	4,56
AST	24,39	5,82	13,15	7,05	17,53/-23,15	2,72	3,21

For horizontal forces (study 1.1), AST shows 8% higher stiffness than ASS, however, vertical forces (study 2) shows that ASS has 1% higher stiffness than ASTs. For cyclic load test, the ductility for ASS is 42% higher than AST. Meaning, ductility is better for the SWP material in this configuration, but for the monotonic load test, the differences are not as big.

HSS vs HST

Table 5-4 compares test group HSS and HST. These groups have horizontal connector angle and 5,0x90mm screw connector type, but different middle sill material.

Table 5-4: Results from HSSs and HSTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
HSS	19,79	11,02	7,77	13,83	15,01/-22,63	2,85	6,99
HST	26,32	11,03	11,46	21,18	17,08/-27,19	2,52	3,64

The results show that HST holds higher maximum load for all the studies, but the stiffness in study 1.1 is similar to HSS. For study 2, HST have higher stiffness (53%) than HSS, meaning that timber C24 sill withstands more under vertical force than SWP material. However, HSS (SWP) is 92% more ductile than HST (timber C24).

During the experiment it was observed that most of the time, the screws in HSS test group were located between the lamellas of the SWP product. This resulted in a separation between the lamellas in study 2, giving a smaller resistance to the vertical force. Figure 5-1 is a picture of HSS7s taken during the experiment, displaying the separation of lamellas.

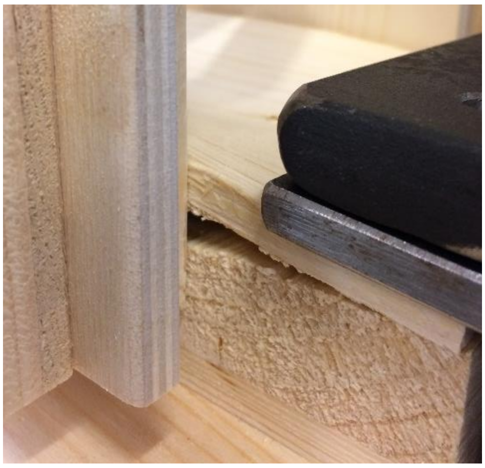


Figure 5-1: Photo of HSS7s during study 2 testing, showing the separation between lamellas in SWP middle sill.

ANS vs ANT

Table 5-5 compares test group ANS and ANT. These groups have angular connector angle and 3,1x90mm nails as connector type, but different middle sill material.

Table 5-5: Results from ANSs and ANTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
ANS	14,06	7,39	5,72	7,24	9,00/-12,87	1,88	3,85
ANT	11,72	6,01	4,56	4,81	8,26/11,63	2,09	5,39

The test group with SWP material (ANS) have higher results in maximum force and stiffness in study 1.1 and study 2. However, ANT is 40% more ductile than ANS.

HNS vs HNT

Table 5-6 compares HNS and HNT. These groups have a horizontal connection angle with 3,1x90mm nail connector types.

Table 5-6: Results from HNSs and HNTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
HNS	11,01	8,63	5,50	4,53	8,02/-10,95	2,62	9,93
HNT	11,40	6,72	5,67	2,90	8,43/-12,15	1,66	3,38

HNS have higher stiffness for both study 1.1 and study 2 compared to HNT. It is also 193,8% more ductile than HNT in study 1.2.

5.1.2 Angular connector VS Horizontal connector

In this section, we compare test groups with the same middle sill material and connector type but with different connector angles, 60° and 90° angle to the outer panels grain of the Termowood element, referred to as angular and horizontal, respectively.

ASS vs HSS

Table 5-7 compares the results from ASS and HSS. The groups have both 5,0x90mm screws as connector type and SWP material as middle sill.

Table 5-7: Results from ASSs and HSSs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
ASS	26,65	5,40	12,40	7,12	19,40/-30,59	2,94	4,56
HSS	19,79	11,02	7,77	13,83	15,01/-22,63	2,85	6,99

The test group with angular connectors (ASS) have higher maximum load. However, HSS have approximately 100% higher stiffness for both study 1.1 and study 2 compared to ASS. For the cyclic load test HSS is 53 % more ductile than ASS.

AST vs HST

Table 5-8 compares test groups AST and HST. The groups have 5,0x90mm screw connectors and timber C24 as middle sill material.

Table 5-8: Results from ASTs and HSTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
AST	24,39	5,82	13,15	7,05	17,53/-23,15	2,72	3,21
HST	26,32	11,03	11,46	21,18	17,08/-27,19	2,52	3,64

The horizontal connector angle (HST) has much higher stiffness for the monotonic load test (i.e. 90% and 200% higher for study 1.1 and study 2) compared to AST, even though the angular connector angle (AST) have close to equal maximum load. The cyclic load test results show that the ductility for HST is 13% higher than AST.

ANS vs HNS

Table 5-9 compares ANS and HNS. The groups have 3,1x90mm nails as connector type and SWP material for the middle sill.

Table 5-9: Results from ANSs and HNSs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
ANS	14,06	7,39	5,72	7,24	9,00/-12,87	1,88	3,85
HNS	11,01	8,63	5,50	4,53	8,02/-10,95	2,62	9,93

ANS have higher maximum load values and has 60% higher stiffness values in study 2 (vertical forces) than HNS. However, HNS has 17% higher stiffness values in study 1.1 (horizontal forces). For the cyclic load test, HNS are 158% more ductile than ANS.

ANT vs HNT

Table 5-10 compares ANT and HNT. The groups contain 3,1x90mm nail connectors and timber C24 as middle sill.

Table 5-10: Results from ANTs and HNTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
ANT	11,72	6,01	4,56	4,81	8,26/-11,63	2,09	5,39
HNT	11,40	6,72	5,67	2,90	8,43/-12,15	1,66	3,38

HNT has 12% higher stiffness values than ANT in terms of horizontal forces (study 1.1). However, study 2 show that ANT has 66% higher stiffness values than HNT. For the cyclic load test, the ductility of ANTc is 60% more ductile than HNTc.

5.1.3 Nails VS Screws

In this section, we compare test groups that have the same middle sill material and connector angle, but different connector types. The comparison is meant to give an overview over each test groups performance. It is important to keep in mind that the dimensions of each connectors are different.

ASS vs ANS

Table 5-11 compares the results for test group ASS and ANS. These groups both have angular connection angle and SWP material as middle sill. Their differences are 5,0x90mm screws (ASS) and 3,1x90mm nails (ANS).

Table 5-11: Results from ASSs and ANSs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
ASS	26,65	5,40	12,40	7,12	19,40/-30,59	2,94	4,56
ANS	14,06	7,39	5,72	7,24	9,00/-12,87	1,88	3,85

The test group with screws (ASS) withstands greater maximum load than ANS. However, ANS has 37% and 2% higher stiffness values than ASS in terms of study 1.1 (horizontal forces) and study 2 (vertical forces), respectively. For the cyclic load test, ASS has 19% higher ductility value than ANS.

AST vs ANT

Table 5-12 compares AST and ANT. The groups have angular connector angles and timber C24 as middle sill material. AST is the group with screw connectors and ANT is with nails.

Table 5-12: Results from ASTs and ANTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
AST	24,39	5,82	13,15	7,05	17,53/-23,15	2,72	3,21
ANT	11,72	6,01	4,56	4,81	8,26/-11,63	2,09	5,39

The results show that AST has greater maximum load than ANT. The stiffness values from study 1.1 (horizontal forces) show that ANT is 3% higher than AST. However, from study 2 (vertical forces) the stiffness for AST is 47% greater than ANT. From the cyclic load test, ANT is 68% more ductile than AST.

HSS vs HNS

Table 5-13 compares results between test group HSS and HNS. The groups both have horizontal connector angle and the middle sill is of SWP material. HSS is the group with screw connectors and HNS is with nails.

Table 5-13: Results from HSSs and HNSs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
HSS	19,79	11,02	7,77	13,83	15,01/-22,63	2,85	6,99
HNS	11,01	8,63	5,50	4,53	8,02/-10,95	2,62	9,93

HSS have larger maximum load than HNS. The stiffness from both study 1.1 and 2 show that HSS is 28% and 205% greater than HNS. However, HNS show 42% higher ductility value than HSS.

HST vs HNT

Table 5-14 compares HST and HNT. The groups have horizontal connector angle and timber C24 as middle sill material in common. HST is the group with screw connector and HNT with nails.

Table 5-14: Results from HSTs and HNTs for monotonic load test (study 1.1 and 2) and cyclic load test (study 1.2). Results retrieved from NS-ISO 6891 (1991) and NS-EN 12512 (2002) calculations.

	Monotonic load test				Cyclic load test		
	Study 1.1		Study 2		Study 1.2		
	Maximum load	Slip modulus	Maximum load	Slip modulus	Maximum load	Slip modulus	Ductility
	kN	*kN/mm*	*kN*	*kN/mm*	*kN (tension/ compression)*	*kN/mm*	-
HST	26,32	11,03	11,46	21,18	17,08/-27,19	2,52	3,64
HNT	11,40	6,72	5,67	2,90	8,43/-12,15	1,66	3,38

The table show that HST have larger maximum load than HNT. The stiffness values for HST is 64% and 630% greater than HNT for study 1.1 (horizontal forces) and study 2 (vertical forces), respectively. For the cyclic load test, the ductility values are less different, were HST is 8% more ductile than HNT.

5.2 Yield point methods – Monotonic load tests

Study 3 is omitted from the discussion, since the test group do not contain any mechanical fasteners and is a special case to calculate values.

NS-ISO 6891 (1991) states that the maximum displacement should be 15 mm, but as observed from NS-EN 12512 (2002), the maximum displacement is set at 30 mm. According to Piazza et al. (2011) and NS-EN 12512 (2002), the maximum displacement stated from NS-ISO 6891 (1991) is considered too low to appreciate the post-elastic capacity of the joint subjected to monotonic load. This is important to keep in mind when comparing the calculations from NS-ISO 6891 (1991) to the other standards.

It was complicated to decide whether to use method (a) or (b) from NS-EN 12512 (2002), since there are many test specimen, that required calculation. Method (a) were neglected due to many load-displacement curves that did not have two well-defined linear parts. Piazza et al. (2011) supports this argument, stating that the method is vaguely describes where these straight lines should be located, and lacks an automatic procedure to implement into a computerized process. The calculations for the thesis needed to be incorporated with a software program, it was easier to choose method (b), referred to as the 1/6 procedure. This procedure is more accurately described and easier to numerically calculate with a software program (e.g. R).

Piazza et. al (2011) implies that the choice of method (a) and (b) affects the results of the yield values obtained from NS-EN 12512 (2002) and as a consequence, influences the calculation of the ductility value. Nevertheless, the influence is not discussed any further.

Study 1.1

Table 5-15 presents the values for yield load, yield slip and ductility from each yield point calculation method done for study 1.1 (monotonic load test). Note that from Yasumura and Kawai method used in NS-ISO 6891 (1991), have no ductility values, since NS-ISO 6891 (1991) do not state any specific ultimate slip, making it difficult to define the ductility ratio.

Table 5-15: Comparison of yield points and ductility ratios from different calculation methods on the monotonic load tests study 1.1.

Method	Standards	Property	Test group from study 1.1							
			ANSs	ANTs	ASSs	ASTs	HNSs	HNTs	HSSs	HSTs
EEEP	EN 12512 (2018) Draft	F_y	13,29	10,75	24,21	22,04	10,34	11,09	18,70	24,45
		v_y	2,20	2,09	5,57	4,60	1,43	1,92	2,06	3,31
		D	14,09	14,49	5,16	6,32	20,35	15,56	14,71	8,37
1/6 procedure	NS-EN 12512 (2002)	F_y	8,00	6,32	19,83	16,09	5,76	6,51	9,88	14,46
		v_y	1,21	1,08	4,45	3,31	0,69	1,00	0,96	1,84
		D	26,26	28,17	6,49	9,08	42,37	30,13	31,80	16,57
Y&K	NS-ISO 6891 (1991)	F_y	6,63	6,05	11,16	10,38	5,92	6,46	9,83	13,03
		v_y	1,18	1,17	2,24	2,08	0,88	1,24	1,29	1,82
		D	–	–	–	–	–	–	–	–

The table above shows that the ductility between EEEP and 1/6 procedure deviates. The 1/6 procedure have an average of 83% higher ductility value than EEEP procedure. This is due to the yield points always being lower than the yield points retrieved from EEEP. Furthermore, the yield point values from Y&K method tend to give the smallest values, relative to the other methods.

Figure 5-2 and figure 5-3 show load-displacement curves from two specimen of different test groups. For simplicity, only two test groups were displayed to exemplify the trend of different yield point methods. The selection is based on initial stiffness, with one low and one high value, to assess how different yield points are affected. The concept arises from Muñoz et al. (2008), discussing the change in yield point values with changes in the initial stiffness.

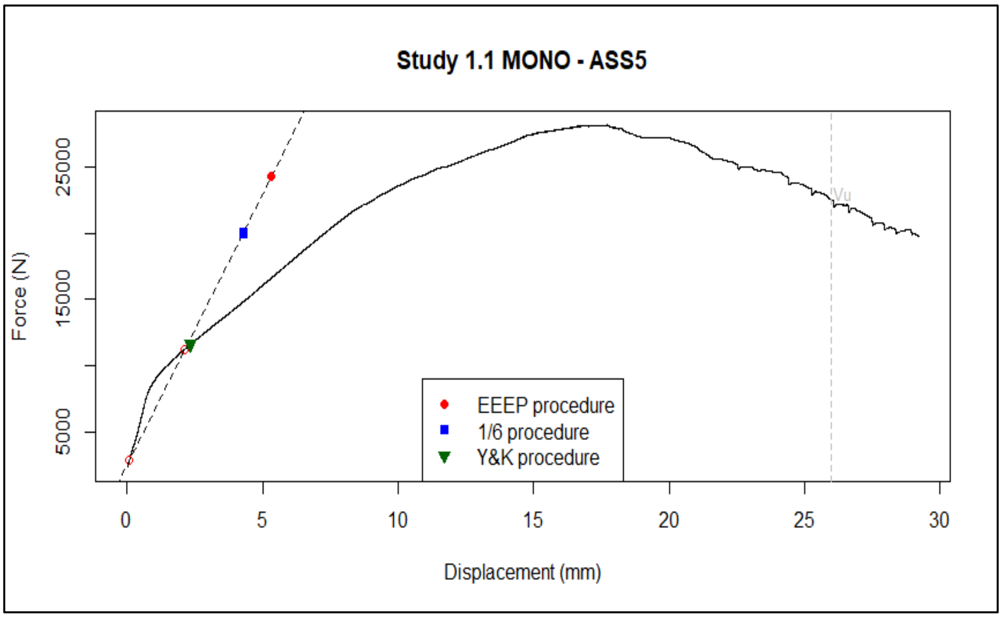


Figure 5-2: Yield points plotted from different calculation methods on test specimen ASS5s for study 1.1

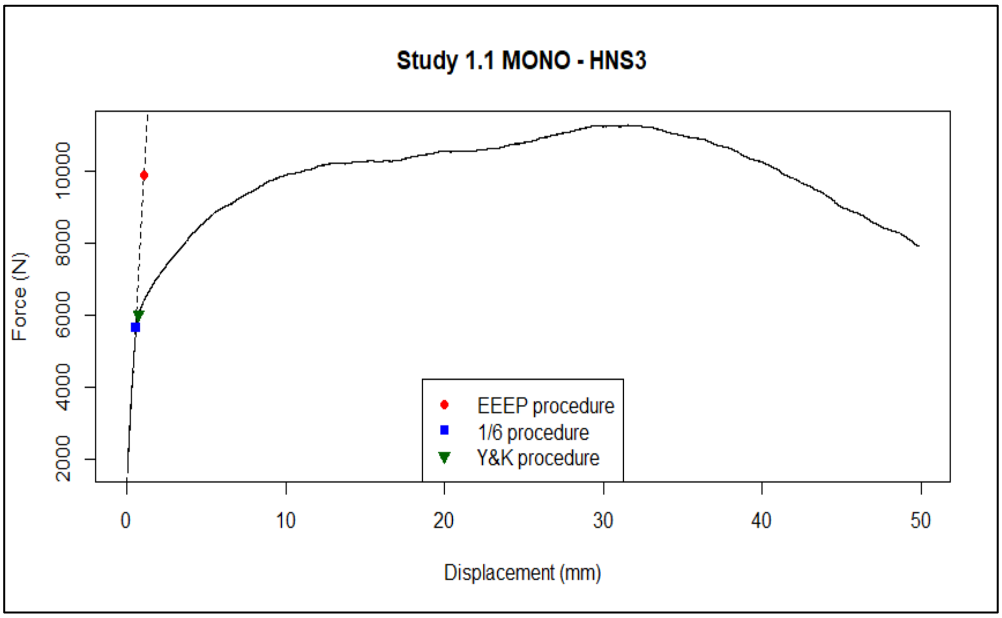


Figure 5-3: Yield points plotted from different calculation methods on test specimen HNS3s for study 1.1

The EEEP procedure is always located way off the load-displacement graph, which is in line with Muñoz et al. (2008) findings. The 1/6 procedure indicates that the yield point is contingent on the stiffness value (i.e. the slope of the line that goes through 10% and 40% of the maximum load). When the stiffness is lower, the yield point derived from the 1/6 procedure tends to go off the load-displacement graph. As for the Y&K procedure, the yield point is not affected by the stiffness value, and mostly stays on the curve.

Study 2

Table 5-16 presents the values for yield load, yield slip and ductility from each yield point calculation method for study 2. Observe that for the calculations done from NS-ISO 6891 (1991), the procedure used is from the standard, referred to as ISO-procedure. The procedure calculates with preload stage displacements retrieved from the load protocol of study 2. Although there are no evident calculations for yield load and ductility in this standard, it might be possible to use other methods to retrieve them, but I choose to stay true to the standard as much as possible.

Table 5-16: Comparison of yield points and ductility ratios from different calculation methods on the monotonic load tests study 2.

Method	Standards	Property	Test group from study 2.							
			ANSs	ANTs	ASSs	ASTs	HNSs	HNTs	HSSs	HSTs
EEEP	EN 12512 (2018) Draft	F_y	5,38	4,18	10,99	11,82	4,52	5,01	6,71	9,75
		v_y	1,28	1,10	2,20	2,19	1,37	2,05	2,19	3,80
		D	8,92	14,46	5,17	5,80	8,85	9,00	4,16	4,69
1/6 procedure	NS-EN 12512 (2002)	F_y	4,61	3,48	9,00	10,01	2,54	2,79	4,90	6,48
		v_y	1,11	0,94	1,84	1,90	0,89	1,29	1,80	2,61
		D	10,30	17,52	6,25	6,80	14,02	14,44	5,39	7,20
ISO-procedure	NS-ISO 6891 (1991)	F_y	–	–	–	–	–	–	–	–
		v_y	0,33	0,28	0,72	0,71	0,39	0,58	0,40	0,92
		D	–	–	–	–	–	–	–	–

The table shows the same trend for study 2 as for study 1.1, where the ductility are higher and yield points are lower from 1/6 procedure compared to EEEP procedure. The 1/6 procedures average difference shows 34,6% higher ductility value than EEEP procedure. As for the ISO-procedure, the yield slip values tend to be much lower than for the other procedures.

Figure 5-4, figure 5-5 and figure 5-6 visualizes load-displacement curves from three specimens of different test groups. For simplicity, only three test groups were displayed to clarify the trend of this study that deviates from study 1.1. The selection is based on observations, such as how the shape of the load-displacement curve affects the different yield point methods and two examples on difficulties defining the stiffness line and failure in the graph. The observations were not visible for study 1.1. Although the ISO-procedure does not have a yield point, it is represented with an orange dashed line to display the yield slip compared to the other yield point results.

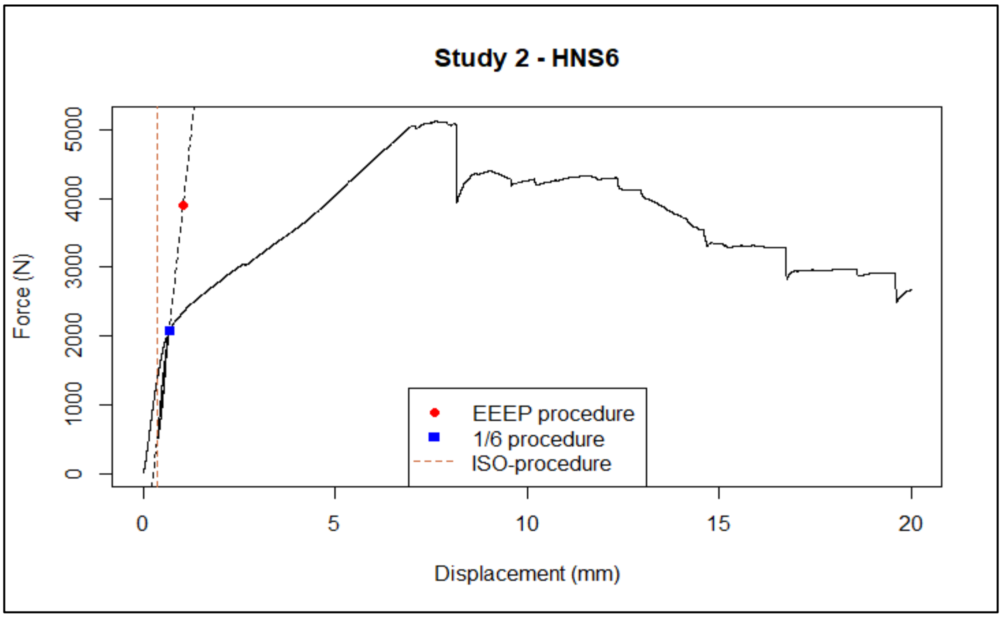


Figure 5-4: Yield points plotted from different calculation methods on load-displacement curve for test specimen HNS8s for study 2.

Figure 5-4 visualizes the same trend as for study 1.1, where the yield point from the EEEP procedure tends to be much higher and off the load-displacement curve. It is on average 40% higher than the 1/6 procedure for specimen HNS6s. Another observation of interest is the shape of the load-displacement curve. The curve has a small convex shape between the yield point of 1/6 procedure and maximum load of the graph, which seems to affect the placement of the 1/6 angled line, placing it almost always tangent to the curve close to the point of $0{,}4 \cdot F_{max}$ (i.e. the second point defining the stiffness line). This shape occurs in HNS3s, HNS5s, and HNS8s, giving the same outcome of yield point placement on the curves.

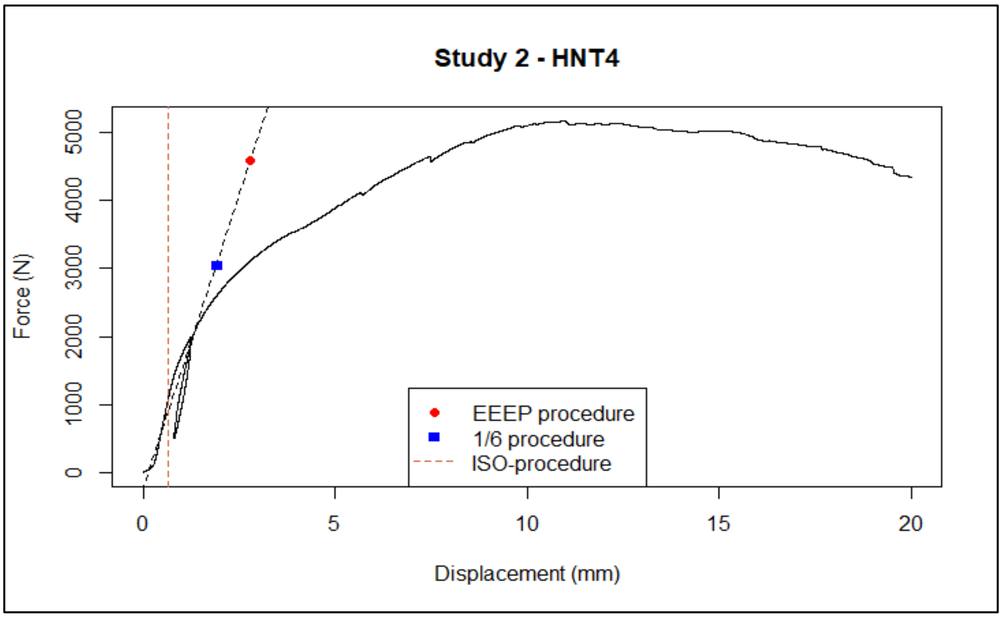


Figure 5-5: Yield points plotted from different calculation methods on load-displacement curve for test specimen HNT8s for study 2.

Figure 5-5, displays the difficulties of defining the first point of the initial stiffness line (i.e. 10 % maximum load). Due to the preload stage from study 2, the point can be derived from two places. The first place is in the beginning of the preload stage, or the second, placed from the end of the preload stage where the main-load stage begins. An argument is to draw the point from the end of the preload stage, since the stage is meant to settle the material and is not a part of the main test. Nevertheless, this is not specified in any standards, making the decision to be up to the experimenter, affecting the slope of the stiffness line. In the figure above, the location of the point (i.e. 10% maximum load) is placed at the beginning of the preload stage. In addition, the figure above visualizes the yield slip from the ISO-procedure, which tends to be very small compared to the EEEP and 1/6 procedure.

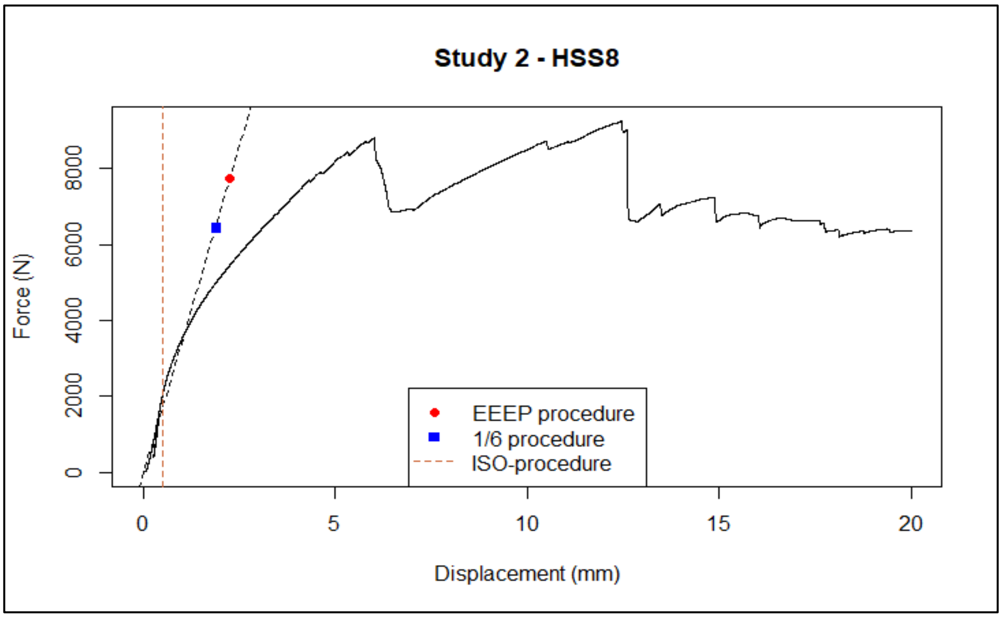


Figure 5-6: Yield points plotted from different calculation methods on load-displacement curve for test specimen HSS8s for study 2

Figure 5-6 is included to discuss the uncertainties of placing failure when calculating. The standards specify that the ultimate load is defined either from failure, 80 % maximum load or 30 mm slip (or degradation factor) whichever occurs first, depending on the standard. For this experiment, the specimen did not break completely off in such way that it was impossible to continue the test. Instead, the specimen was always able to take some load force from the Instron machine after an observed load drop in the graph. Particularly for the test group HSS, where none of the connectors broke, meaning that it was the SWP material in the middle sill that yielded.

For the calculation, it was decided to describe failure as the load drop where the specimen could not obtain higher force resistance after this point. Applying this to figure 5-6, the failure would be the second big load drop (counted from the left), since the specimen were able to maintain a higher force resistance after the first load drop. This is consistently being chosen for all monotonical load tests, even though it might not be a correct way of describing failure according to the standards.

Study 3

Table 5-17 presents the values for yield load, yield slip and ductility from each yield point calculation methods for study 3. Note that the test group without fasteners (WOF) is not included since there are no fasteners to evaluate.

Table 5-17: Comparison of yield points and ductility ratios from different calculation methods on the monotonic load tests study 3.

Method	Standards	Property	Test group from study 3
			WFs
EEEP	EN 12512 (2018) Draft	F_y	22,59
		v_y	1,84
		D	6,17
1/6 procedure	NS-EN 12512 (2002)	F_y	15,59
		v_y	1,43
		D	10,97
ISO-procedure	NS-ISO 6891 (1991)	F_y	–
		v_y	0,51
		D	–

The ductility and yield points follow the trend as for study 1.1 and 2. Figure 5-7 presents the load-displacement curve from specimen WF2, the other specimen from the same group are similar. The yield points from different calculation procedures are displayed in the figure, observing the same trends as discussed earlier, where the yield point from EEEP procedure is higher than 1/6 procedure, and the yield slip from ISO-procedures is much lower than the others.

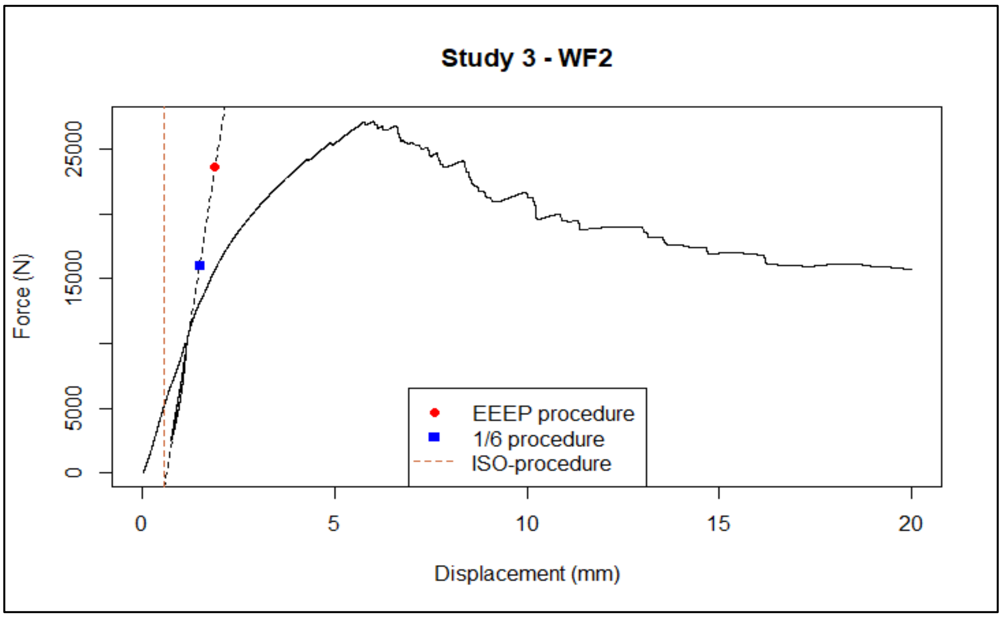


Figure 5-7: Yield points plotted from different calculation methods on load-displacement curve for test specimen WF2s from study 3.

5.3 Yield point methods – Cyclic load tests

Table 5-18 presents the values for yield load, yield slip and ductility from each yield point calculation methods for study 1.2 – cyclic load test.

Table 5-18: Comparison of yield points and ductility ratios from different calculation methods on the cyclic load tests, study 1.2.

Method	Standards	Property	Test group study 1.2							
			ANSc	ANTc	ASSc	ASTc	HNSc	HNTc	HSSc	HSTc
EEEP	EN 12512	F_y	6,50	6,27	17,54	15,22	6,45	7,12	11,87	14,98
	(2018)	V_y	3,2	3,62	6,98	5,68	3,29	4,32	4,17	6,74
	Draft	D	2,88	3,44	2,96	2,67	5,67	2,41	4,04	2,49
1/6 procedure	NS-EN	F_y	6,84	5,83	15,29	14,72	4,79	7,22	10,74	12,92
	12512	V_y	4,0	3,9	6,4	5,5	2,8	4,7	4,3	6,0
	(2002)	D	3,85	5,39	4,56	3,21	9,93	3,38	6,99	3,64

The 1/6 procedures average differences show 50% higher ductility values than the EEEP procedure. Which is a lower deviation than study 1.1, but higher than study 2, although stating the same trend (i.e. 1/6 procedure ductility is higher than EEEP). For some test groups (i.e. ANS and HNT), the yield load from the EEEP method is lower than 1/6 procedures yield load, which was never the case in monotonic load tests.

The location of yield points on the positive side of the cyclic load test (i.e. tension load) is shown in figure 5-8, figure 5-9 and figure 5-10. They represent a selection of three different test groups (i.e. ASS, HNS and HSS), displaying three different variations of the yield point locations.

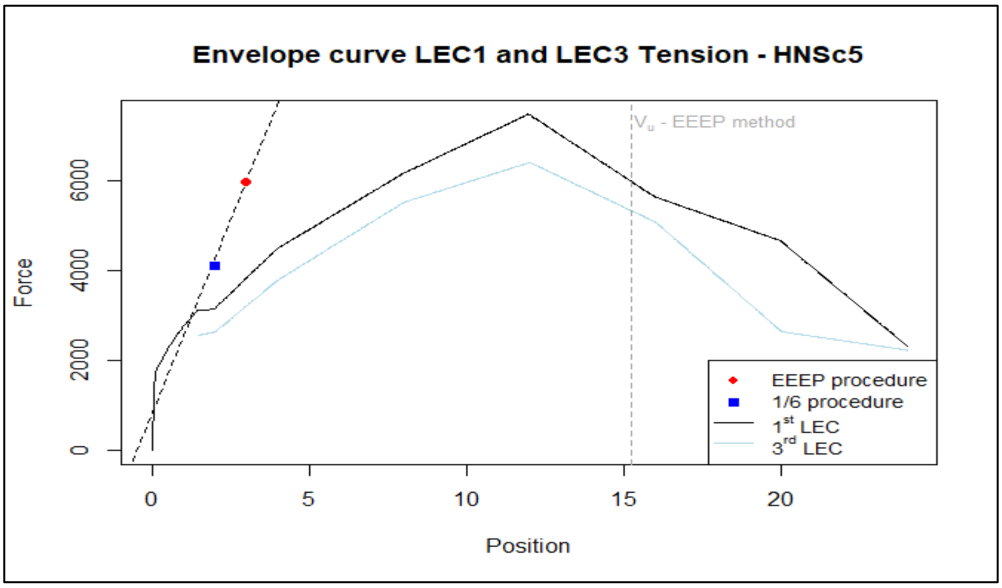


Figure 5-8: Yield points plotted from different calculation methods on positive load-displacement curve for test specimen HNS5c from study 1.2.

Relative to figure 5-9, deviates the yield points in figure 5-8 more when the stiffness is higher. Stating that increased stiffness gives increasing deviations between yield points. In addition, EEEP procedures yield point is higher than for the 1/6 procedure. These trends are the same for the monotonic load test.

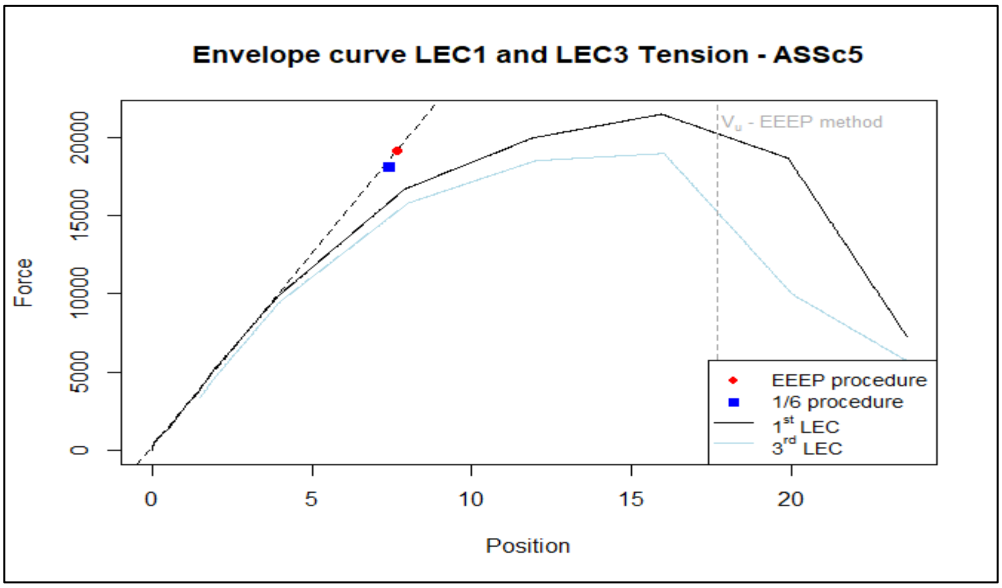


Figure 5-9: Yield points plotted from different calculation methods on positive load-displacement curve for test specimen ASS5c from study 1.2.

In figure 5-9, the two yield points from each method are in nearly the same location. This situation follows the same trend as for the monotonic load test calculations, where the slope of the stiffness line is lower. This affect the 1/6 procedure to fall off the load-displacement curve and positions closer to the EEEP yield point. However, these two situations are when the ultimate displacements are similar for both calculations, e.g. 20,5mm and 17,7mm for the 1/6 procedure and EEEP procedure respectively in figure 5-9. Figure 5-10 visualizes load-displacement curve for specimen HSS5c, where the ultimate displacement of the EEEP procedure is lower than the 1/6 procedure.

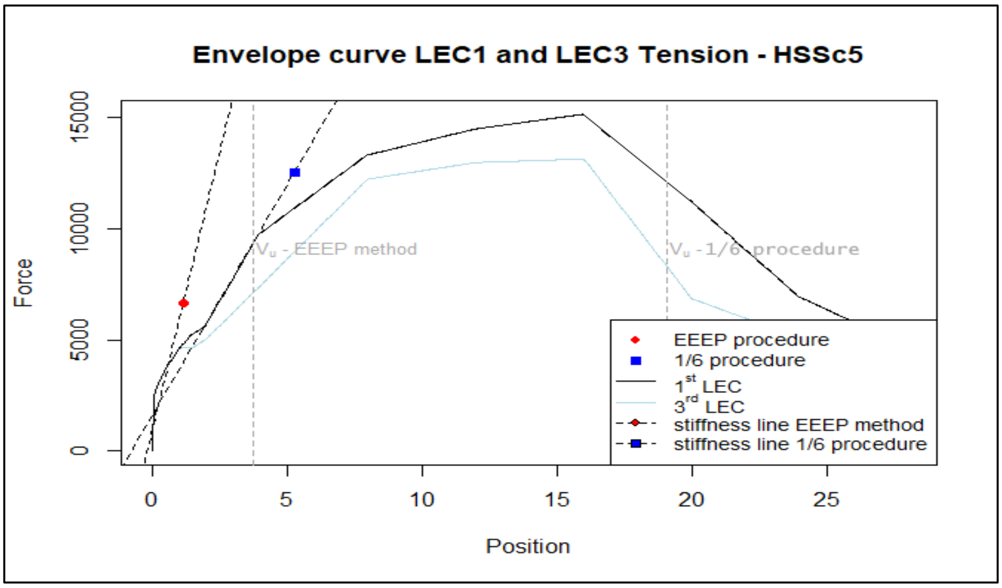


Figure 5-10: Yield points plotted from different calculation methods on positive load-displacement curve for test specimen HSS5c from study 1.2.

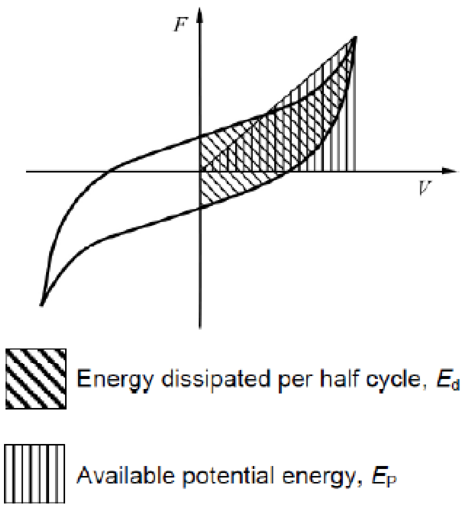
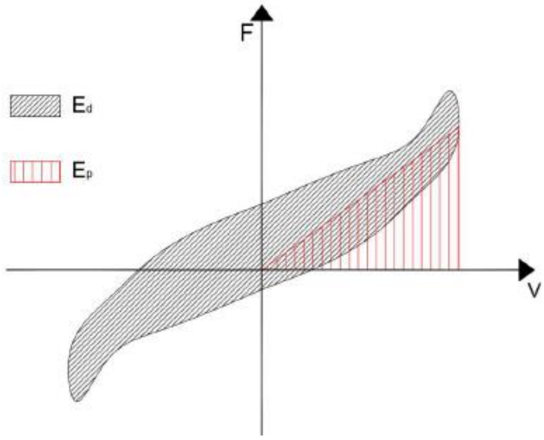
The yield point from EEEP procedure is lower than the yield point from 1/6 procedure. The ultimate displacements deviate from each other, resulting in different slopes for the stiffness line, which generate different yield points. The differences in ultimate displacement is due to the new description of the value in EN 12512 (2018) Drafts, where the degradation factor positions the ultimate displacement lower than the other (i.e. 1/6 procedure). The degradation factor is not represented in the other standards. Also, the definition of the stiffness line is slightly different in the new draft proposal, where they calculate it from the maximum load reach for displacements lower than the ultimate displacement. In contrast, NS-EN 12512 (2002) calculates the stiffness line with the maximum load reach during the whole test (called peak load in EN 12512 (2018) Draft).

However, the ductility values for specimen HSS5c shows that the differences are small between the two methods, that is 3,67 and 3,21 for the 1/6 procedure and the EEEP procedure, respectively. Although the yield points vary, the deviations between each calculation methods yield approximately the same ductility values. This may be due to the definition of the ductility ratio, which depends on ultimate displacement and yield slip. When they both changes relatively the same, the changes in ductility do not vary as much.

5.4 Equivalent viscous damping ratio

Based on the results from study 1.2, figure 4-2 visualizes the equivalent viscous damping ratio from NS-EN 12512 (2002) and EN 12512 (2018) Draft. The comparison shows a difference in viscous damping values between the methods. The viscous damping values calculated from the draft proposal seem to consistently be higher than (2002) standard.

Table 5-19: Overview over equivalent viscous damping ratio definitions from NS-EN 12512 (2002) and EN 12512 (2018) Draft.

	
$\nu_{eq} = \frac{E_d}{2\pi \cdot E_p}$ (8)	$\nu_{eq,c} = \frac{E_d}{4\pi \cdot E_p}$ (11)
NS-EN 12512 (2002)	EN 12512 (2018) Draft

If we consider the definitions in the two standards shown in table 5-19, we can see that the new draft proposal (right) evaluates the dissipated energy with the entire cycle, while NS-EN 12512 (2002) standard (left) only evaluates the half cycle. However, the equations make the inequality of the definitions irrelevant. The differences may be due to the cycles symmetry between tension and compression force (negative and positive values in the graph), since the cyclic load-displacement curves in this experiment were not as symmetric as expected. This is discussed further in section 5.6 *Implications and limitations.*

5.5 Equations derived for EN 12512 (2018) Draft

This chapter describes and verifies the equations derived for calculating the EEEP curve and equivalent viscous damping ratio when following the procedures from EN 12512 (2018) Draft version n°20180410.

EEEP curve calculations

The EEEP curve is the Equivalent Energy Elastic-Plastic curve determined from the 1st load envelope curve in a cyclic load test. As explained in chapter 2.2.3, the stiffness (K), yield load (F_y) and yield displacement (V_y) is obtained from this curve. The stiffness is retrieved by drawing through the points and calculating the slope corresponding to $0{,}1 \cdot F_{max}$ and $0{,}4 \cdot F_{max}$. This line, a horizontal line and the boundary from origin to the ultimate displacement, outlines the EEEP curve (figure 5-11). The horizontal line is obtained when the area under the 1st envelope curve is equal to the area under the EEEP curve and can be expressed as:

$$A_{LEC1} = A_{EEEP} \quad (19)$$

In other words, the y-value of the horizontal line must be determined so that the area under the EEEP curve is equal to the area of the 1st envelope curve. This line is the variable to be solved for and the solution is to use integral calculations of the area under the EEEP curve. The yield load and yield displacement are the intersection between the horizontal line and the line going through 0,1 and $0{,}4 \cdot F_{max}$.

To find an expression of the area, the EEEP curve is divided into two polygons, a triangle (A_1) and a rectangle (A_2) . The total area of the EEEP curve is then the sum of these two polygons area.

$$A_{EEEP} = A_1 + A_2 \quad (20)$$

We want to solve for the boundary conditions for the integrals, when calculating the area. Figure 5-11 visualizes the EEEP curve with boundary conditions and variables.

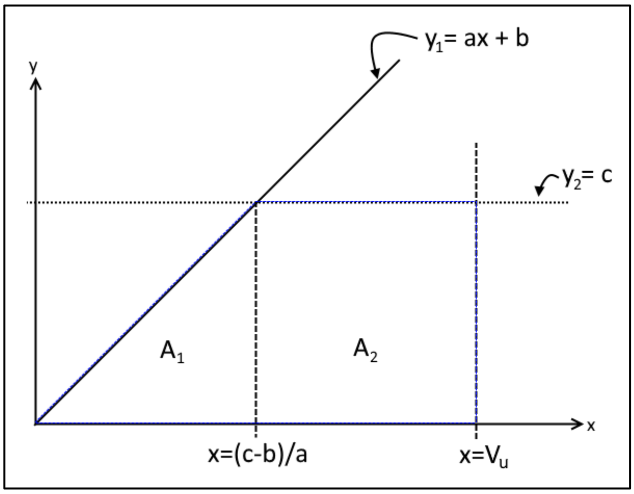


Figure 5-11: Overview of calculation of the yield point with EEEP curve procedure.

The polygons A_1 and A_2 are calculated as the area under the lines y_1 and y_2, respectively. Giving the integral equation of the total area to be:

$$A_{EEEP} = \int y_1 dx + \int y_2 dx \tag{21}$$

For the polygons area, the integral equations with boundaries are as follows:

$$A_1 = \int_0^{\frac{c-b}{a}} (ax + b) dx \tag{22}$$

$$A_2 = \int_{\frac{c-b}{a}}^{V_u} c\, dx \tag{23}$$

Where a is the slope and b is the y-intercept of the line y_1, V_u is the value at ultimate displacement and c is the horizontal line, y_2. Solving the integrals, we get,

$$A_1 = \frac{1}{2a}(c^2 - b^2) \tag{24}$$

$$A_2 = c\left(V_u - \frac{c}{a} + \frac{b}{a}\right) \tag{25}$$

Solving equation (24) and (25) in the total area equation (20), we get an expression of the EEEP area to be,

$$A_{EEEP} = \frac{1}{2a}(c^2 - b^2) + c\left(V_u - \frac{c}{a} + \frac{b}{a}\right) \tag{26}$$

Where the variable c is the value we want to solve for, to find the horizontal line, y_2. Solving the equation for c with the quadratic equation, gives the following expression,

$$c = a \cdot \left(\left(V_u + \frac{b}{a} \right) \pm \sqrt{\left(V_u + \frac{b}{a} \right)^2 - 4 \left(\frac{b^2}{4a^2} + \frac{A_{EEEP}}{2a} \right)} \right) \tag{27}$$

Since the area of the EEEP curve must be equal to the area under the 1st envelope curve, we can rewrite the equation as,

$$c = a \cdot \left(\left(V_u + \frac{b}{a} \right) \pm \sqrt{\left(V_u + \frac{b}{a} \right)^2 - 4 \left(\frac{b^2}{4a^2} + \frac{A_{LEC1}}{2a} \right)} \right) \tag{28}$$

The equation is a quadratic expression, giving two different values of c. The equation solved with plus-sign ends up with a value larger than the peak load, which is outside the graph and is therefore neglected. This gives us the equation that draws the EEEP curve with the area equal to A_{LEC1},

$$c = a \cdot \left(\left(V_u + \frac{b}{a} \right) - \sqrt{\left(V_u + \frac{b}{a} \right)^2 - 4 \left(\frac{b^2}{4a^2} + \frac{A_{LEC1}}{2a} \right)} \right) \tag{29}$$

To verify the equation above, equation 2 from Muñoz et al. (2008) has a similar approach to calculate yield load in EEEP curve. The equation is as follows,

$$P_y = \left[\Delta_{failure} - \sqrt{\Delta_{failure}^2 - \frac{2w_{failure}}{K}} \right] \cdot K \tag{30}$$

Where P_y is yield load, $\Delta_{failure}$ is the ultimate displacement at failure, $w_{failure}$ is the area under the 1st envelope curve with boundaries from zero to ultimate displacement and K is the elastic stiffness.

If we implement the same variables to our equation (29), our expression will look like,

$$P_y = K \left(\left(\Delta_{failure} + \frac{b}{K} \right) - \sqrt{\left(\left(\Delta_{failure} + \frac{b}{K} \right)^2 - 4 \left(\frac{b^2}{4K^2} + \frac{w_{failure}}{2K} \right) \right)} \right) \tag{31}$$

$$where\ V_u = \Delta_{failure}, a = K, A_{LEC1} = w_{failure}, c = P_y$$

We can now see that the difference between equation 2 from Muñoz et al. and our equation is the y-intercept (b) that is represented in our equation. If we set b = 0, we will retrieve the same equation that Muñoz et al. (2008) is presenting,

$$P_y = K\left(\Delta_{Failure} - \sqrt{\left(\Delta_{failure}^2 - \frac{2w_{failure}}{K}\right)}\right) \tag{32}$$

When b is set at zero, the equation is calculating as if the diagonal line, y_1, is going through the origin. This is not always the case when analysing cyclic load tests. For our equation proposal, the y-intercept, b, is implemented to the equation.

Equivalent viscous damping ratio calculations

This section addresses the solution used to calculate the dissipation of energy from EN 12512 (2018) Draft version n°20180410 for cyclic load tests.

The dissipation of energy, E_d, is the energy in one entire cycle retrieved from cyclic load tests. The available potential energy, E_p, is also evaluated for positive values of displacement. The equivalent viscous damping ratio, ν_{eq}, is then given as,

$$\nu_{eq} = \frac{E_d}{4\pi \cdot E_p} \tag{33}$$

To calculate the dissipation of energy for each cycle using software program, Green's theorem is used to solve the calculations.

With Green's theorem we can determine the area of a region that is formed by an enclosed curve. From the Green's line integral it is possible to derive an equation that solves the area with coordinates of each datapoints. The derived formula is originated from Mathematics Community Blog (2014) and it is useful for software programming.

To find total area with coordinates derived from Green's theorem we have the following formula,

$$A = \sum_{k=0}^{n} \frac{(x_{k+1} + x_k)(y_{k+1} - y_k)}{2} \tag{34}$$

The theorem states that the region must be an enclosed curve and the direction that is calculated must be in a counter-clockwise direction around the curve. To make the cycle curve enclosed must the first and the last datapoints in the dataset be bonded together, and if the direction is opposite we only get the negative value of the correct area.

The R script of the area is written as,

```
area1 <- function(X){
      X <- rbind(X,X[1,])
      x <- X[,1]; y <- X[,2]; lx <- length(x)
      sum(((x[2:lx]+x[1:lx-1])*(y[2:lx]-y[1:lx-1])))/2
      }
```

Where the rbind() function binds the first and the last datapoint to enclose the cycle, and the sum equation is the code of the total area formula.

5.6 Implications and limitations

It is important to keep in mind that the specimen used in the experiment for this thesis is self-made and that the stated angles might not be the accurate angle that are tested for, but an approximation. Moreover, this experiment and analysis is only a representation of the product, but the results are not robust enough to be interpreted as the solid proof. The study should be replicated and serve as a baseline for several experiments, and detailed analyses of the product should be carried out to verify the work of the thesis. Below are some implication and limitations discussed for the calculations and the experiment.

Comments on the calculations

The experiment of Yasumura (1998) describe that the calculation of the slip modulus is taken from the slope of the line going through the points of $0,1 \cdot F_{max}$ and $0,6 \cdot F_{max}$, instead of $0,4 \cdot F_{max}$. It states that the $0,4 \cdot F_{max}$ point is sensible to friction between the timber and steel plates, as a result of the experiments layout. To avoid this effect, $0,6 \cdot F_{max}$ was used instead. In our experiment, we observed friction between the TW element and the bottom sill, as well as the clamping system for the cyclic load test. This may have disturbed the measurements during testing. It may be that our calculated point at $0,4 \cdot F_{max}$ is affected and that a solution like Yasumura (1998) could have been a way to obtain a more precise slip modulus.

During the calculation phase, it was early observed that the calculations from the new draft proposal were easier to program and had more efficient runtime than the other calculated yield point methods. For instance, the coding of moving a line to touch the graph, used by Y&K and the 1/6 procedure, was a challenging task to script. Unlike scripting the EEEP curve, applying a mathematical approach, the runtime was much shorter. The EEEP method was more numerical and direct, making the code more reliable when applied to the data set.

The R script coded for calculating the dataset after EN 12512 (2018) Draft, was tested on a dataset sent from Daniele Casagrande at CNR-IVALSA in Italy. Due to lack of basic information, such as the cyclic amplitude, the R script coded for the envelope curve was plotted manually with a locator, pin-pointing the maximum values for each cycle.

The results are only calculated approximations, but the results showed that the R script were close to Casagrande's results, despite the shortcut. The values from both results are presented in table 5-20.

Table 5-20: Comparison of the R script calculations with Casagrande's results.

90SC10mm_C_001[1153]	Yield slip (mm) v_y	Yield load (kN) F_y	Slip modulus (kN/mm) K_{ser}	Static ductility D	Ultimate displacement (mm)	Peak Load (kN)	Design Strength Degradation Factor β_{sd}
R-script calculations	3,256	77,274	20,73	7,334	23,88	84,65	0,768
Casagrande's results	3,05	77,24	22,76	7,82	23,80	84,90	0,765

The R script used for Casagrande's dataset is presented in Appendix F – R Script.

Comments on the experiment – Study 1.2

As stated earlier, the Instron set-up for the specimens in study 1.2 (cyclic load test) makes the deformation measurements uncertain. One problem is the bottom sill that interfered with the TW element while under compressive load. The friction contaminates the measures of deflection and makes it challenging to discover where the connectors fail. Based on the graphical representation (Appendix C – Study 1.2 (Cyclic Load Test)) it looks like "tags", that can be mistaken for connection failure.

Another issue observed during testing, was an uplift of the specimen during tension force. It seems that the clamping system was sub-optimally designed, since the specimen rose few millimetres of the baseplate. This resulted in an inwards bending of the sills, also contaminating the global deformation measurements. A solution was to tighten the clamping system occasionally and attending to them during the test. This performance showed a small effect, giving better measurements, but the differences were still present. Due to this issue, an asymmetrical deformation in the cyclic amplitudes between the tension and compression side was observed, often making the compressive deformations and loads higher than the tension load. Since the global measurements are measuring the wrong deflections, a solution could have been to use the local deformation measurements in the data analysis. The reason for the absence of the local data measurements, was due to computational input issues from the instruments, where the input only gave deformation values with one decimal number. For this kind of experiment, at least three decimals is needed to enable a good analysis of the raw data.

In addition, the maximum deflection point in some of the available measuring instruments were too small to be applied to the cyclic load test. The instruments could not be applied because of the risk of destroying them, yielding the limited number of instruments used.

As learned from this experiment, the bottom sill could have been dropped from the specimen layout in study 1, and only keep the middle sill connected to the TW element. This kind of geometry may give a more direct measurement on how the sill connectors behave. Also, the clamping system should either be placed closer to the specimen or perhaps benefitted from another design, altogether.

For study 3, there was only one configuration tested with fasteners. The results conducted from this test might be easier to interpret if there were other configurations tested simultaneously, making it possible to compare. In addition, a thorough analysis of the friction between tongue and groove system should be carried out (i.e. test group without fasteners).

5.7 Future research

The research papers Casagrande et al. (2018) and Casagrande et al. (2016) presents an analytical approach on how to numerically model a shear wall. The papers show that the experimental results can be used to make an analytical model of the Termowood product.

Further experimental work based on this experiment, as stated in the previous chapter, can and should be conducted without bottom sill or with another test set-up. If the new draft proposal for EN 12512 is applied, it could be of interest to compare different cyclic load protocol to assess how this relates to the calculations.

In addition, different experimental configurations can be investigated, for instance positioning the SWP middle sill so that the grain of the material is in a better orientation. This will among other things, allow for a better minimum distance of the connectors. Another experimental configuration is to test the product with other connectors, like angle brackets, hold downs or longer inclined screws. Although, the producer does not prefer angel brackets and hold downs, it could be valuable to evaluate the behaviour of the product.

Lastly, if the Termowood product is analysed in detail, the comparison of the test results to other products would enable a deeper understanding of the product.

6 REFERENCES

Binderholz (2018) *Solid Wood and Construction Panels.* Available at: https://www.binderholz.com/fileadmin/PDF/Services_Kontakt/Videos_Download/Prospekte/Massivholz_und_Konstruktionsplatten_GB_WEB.pdf (Accessed: 2018-05-30).

Blaß, H. J., Bejtka, I. and Uibel, T. (2006) 'Tragfähigkeit von Verbindungen mit selbstbohrenden Holzschrauben mit Vollgewinde'.

Blaß, H. J. and Uibel, T. (2007) 'Tragfähigkeit von stiftförmigen Verbindungsmitteln in Brettsperrholz'.

Casagrande, D., Doudak, G., Mauro, L. and Polastri, A. (2018) 'Analytical Approach to Establishing the Elastic Behavior of Multipanel CLT Shear Walls Subjected to Lateral Loads', *Journal of Structural Engineering,* 144(2), pp. 04017193.

Casagrande, D., Rossi, S., Tomasi, R. and Mischi, G. (2016) 'A predictive analytical model for the elasto-plastic behaviour of a light timber-frame shear-wall', *Construction and Building Materials,* 102, pp. 1113-1126.

EN 12512 2018. Draft proposal version n°20180410: Timber Structures - Test Methods - Cyclic testing of timber connections and assemblages for seimic design. *In:* Daniele Casagrande CNR-IVALSA Italy & Maurizio Piazza University of Trento Italy (ed.).

Foliente, G. C. (1996) 'Issues in seismic performance testing and evaluation of timber structural systems', *Proceedings of the 1996 International Timber Engineering Conference, Vol 1, New Orleans, LA, pp. 1.29-1.36.*

Follesa, M., Fragiacomo, M., Casagrande, D., Tomasi, R., Piazza, M., Vassallo, D., Canetti, D. and Rossi, S. (2018) 'The new provisions for the seismic design of timber buildings in Europe', *Engineering Structures,* 168, pp. 736-747.

Foschi, R. O. (1974) 'Load-slip characteristics of nails', *Wood Sci,* 7(1), pp. 69-76.

Fragiacomo, M., Dujic, B. and Sustersic, I. (2011) 'Elastic and ductile design of multi-storey crosslam massive wooden buildings under seismic actions', *Engineering Structures,* 33(11), pp. 3043 - 3053.

Jorissen, A. and Fragiacomo, M. (2011) 'General notes on ductility in timber structures', *Engineering Structures,* 33(11), pp. 2987-2997.

Kucera, B. (1992) *Skandinaviske normer for testing av små feilfrie prøver av heltre.* Skogforsk.

Mathematics Community Blog (2014) *Green's Theorem and Area of Polygons*. By apnorton. Available at: https://math.blogoverflow.com/2014/06/04/greens-theorem-and-area-of-polygons/#more-25 (Accessed: 01.06.2018.

Motek (a) (2018) *Utvendig treskrue med senkhode, C4.* Available at: https://www.motek.no/skruteknikk/treskruer/skruer-til-tre/utvendig-treskrue-med-senkhode-c4 (Accessed: 2018-05-30).

Motek (b) (2018) *Sponskruer torx, løse skruer*. Available at: https://www.motek.no/skruteknikk/treskruer/sponskruer/sponskrue-torx-lose-skruer (Accessed: 2018-05-30).

Motek (c) (2018) *Rundhodet, diamond coating kammet, varmforsinket spiker 17º.* Available at: https://www.motek.no/spikremaskiner-og-spiker/stavspikring/spiker-for-bostitch-n89rh17-n88-motek-prostrip-atro-rhs917-og-spotnailmns5/rundhodet-diamond-coating-kammet-varmforsinket-spiker-17-leveres-i-plastbotte-nyhet (Accessed: 2018-05-30).

Muñoz, W., Mohammad, M., Salenikovich, A. and Quenneville, P. 'Need for a harmonized approach for calculations of ductility of timber assemblies'. *Proceedings of the Meeting*.

NS-EN 1995-1-1 2004. Design of timber structures - Part 1-1: General Common rules and rules for buildings. *Eurocode 5*. Norwegian Standard.

NS-EN 1998-1 2004. NS-EN 1998-1:2004+A1:2013+NA:2014. Standard Norge.

NS-EN 12512 2002. Timber Structure, Test Methods - Cyclic testing of joints made with mechanical fasteners.: Norwegian Standard.

NS-EN 13353 2008. Solid wood panels (SWP) - Requirements. Norwegian Standard.

NS-ISO 6891 1991. Timber Structures, Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics. *In:* EN 26891:1991 (ed.). Norwegian Standard.

Piazza, M., Polastri, A. and Tomasi, R. (2011) 'Ductility of timber joints under static and cyclic loads', *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, 164(2), pp. 79-90.

Stehn, L. and Björnfot, A. 'Comparison of different ductility measures for a nailed steel-to-timber connection'. *World conference on timber engineering: 12/08/2002-15/08/2002*: Penerbitan Publications, 155-162.

Termowood (2017) *Standard constructiondetails for Termowood Element corresponding to SINTEF Building Research Design Guide Technical Approval nr. 20534*. Available at: https://live.termowood.eyego.no/wp-content/uploads/sites/2/2017/01/TG-20534-Std-kontr-det-05mai2017.pdf (Accessed: 2018-05-30).

Uibel, T. and Blaß, H. J. 'Joints with Dowel Type Fasteners in CLT Structures', *Focus Solid Timber Solutions - European Conference on Cross Laminated Timber (CLT), 21.-22.05.2013, TU Graz. Ed.: R. Harris*: TU, Graz, 119-134.

Yasumura, M. (1998) 'Mechanical properties of dowel type joints under reversed cyclic lateral loading', *Proceedings of the CIB-W18 meeting, Savonlinna, 1998*.

Yasumura, M. and Kawai, N. (1997) 'Evaluation of wood framed shear walls subjected to lateral load', *Proceedings of the 30th CIB-W18, Vancouver, Canada, 1997*.

7 APPENDIX

Appendix A – Failure Mode Photos

Study 1.1 – failure mode

Failure mode for study 1.1 and study 2. Arrow indicates direction of load.

Figure A1: ANS study 1.1 failure mode

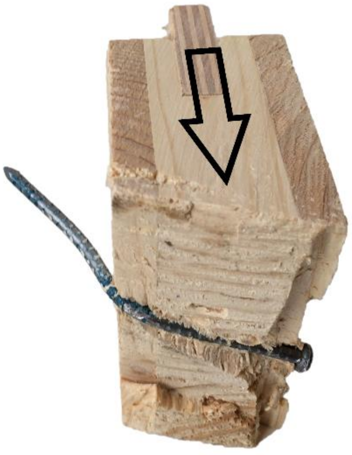


Figure A2: ANT study 1.1 failure mode

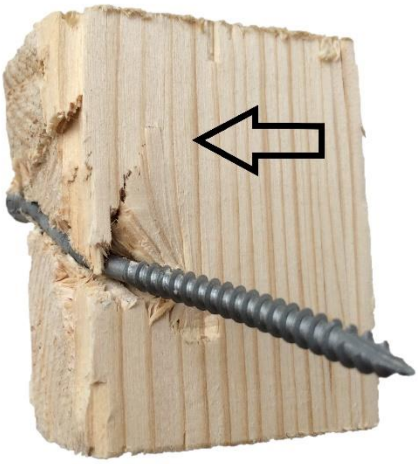


Figure A3: ASS study 1.1 failure mode

Figure A4: AST study 1.1 failure mode

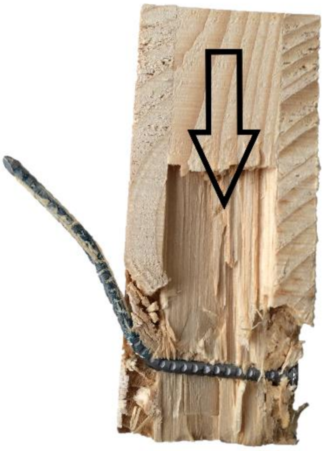
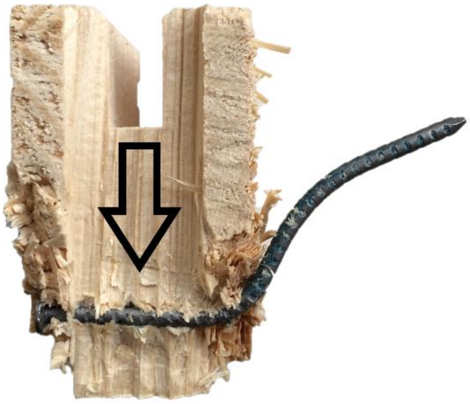
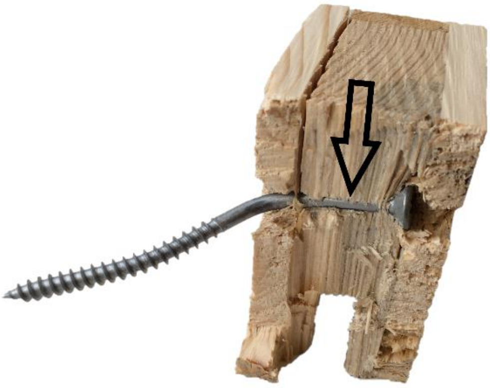
	

Figure A5: HNS study 1.1 failure mode	*Figure A6: HNT study 1.1 failure mode*
	
Figure A7: HSS study 1.1 failure mode	*Figure A8: HST study 1.1 failure mode*

Study 2 – failure mode

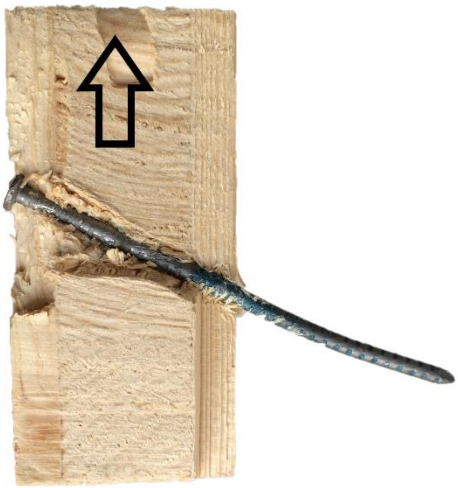


Figure A9: ANS study 2 failure mode	*Figure A10: ANT study 2 failure mode*

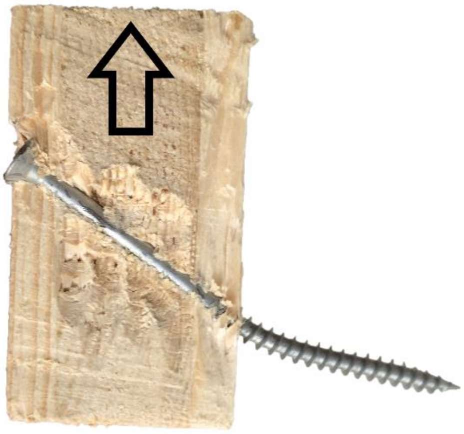


Figure A11: ASS study 2 failure mode

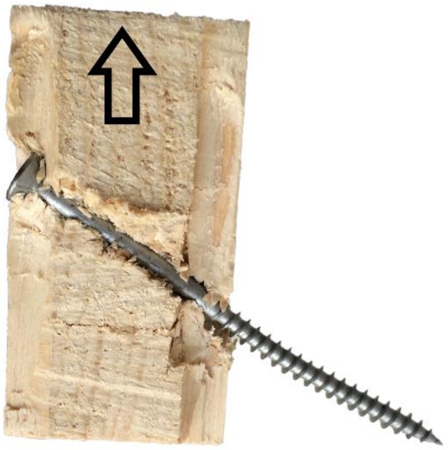


Figure A12: AST study 2 failure mode

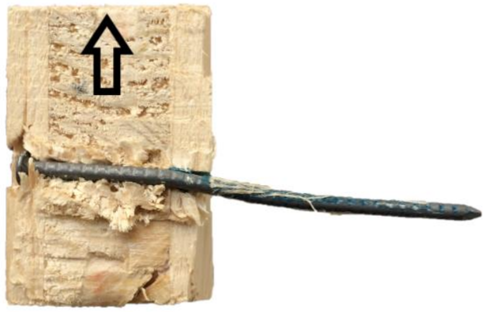


Figure A13: HNS study 2 failure mode

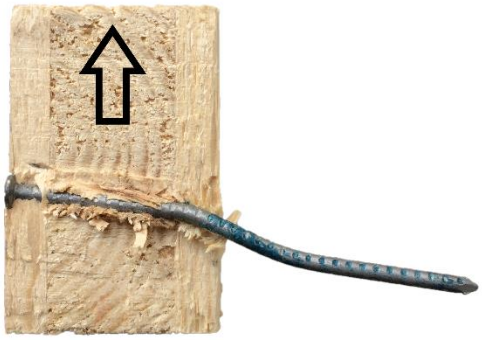


Figure A14: HNT study 2 failure mode

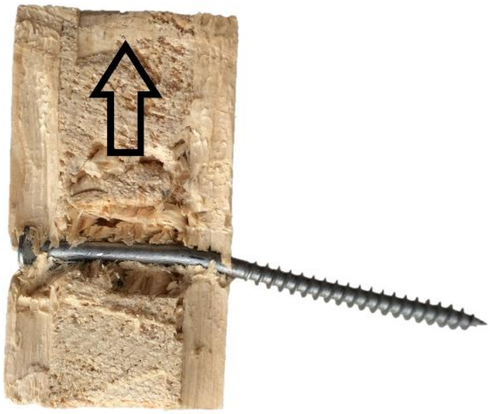


Figure A13: HSS study 2 failure mode

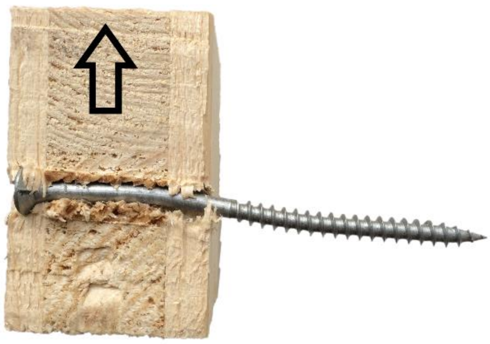


Figure A14: HST study 2 failure mode

Appendix B – Study 1.1 (Monotonic Load Test)

Moisture Content

Moisture content measured with moisturemeter for every specimen in each test group for study 1.1.

Table B1: Moisture content, Study 1.1.

specimen	moisture content % sill1|sill2	specimen	moisture content % sill1|sill2
HST-1s	16,3|15,6	HNS-1s	14,4|13,1
HST-2s	17,1|16,0	HNS-2s	15,7|14,3
HST-3s	15,8|15,9	HNS-3s	14,6|14,1
HST-4s	16,0|16,0	HNS-4s	13,8|14,3
HST-5s	14,6|12,8	HNS-5s	14,7|14,6
HSS-1s	12,4|13,8	HNT-1s	15,7|15,5
HSS-2s	12,2|12,6	HNT-2s	16,7|16,2
HSS-3s	12,0|13,1	HNT-3s	16,7|16,4
HSS-4s	13,9|14,5	HNT-4s	16,0|16,4
HSS-5s	12,3|12	HNT-5s	16,6|15,8
ANT-1s	14,8|15,2	AST-1s	15,5|16,1
ANT-2s	16,3|15,5	AST-2s	15,9|16,5
ANT-3s	16,2|16,2	AST-3s	16,2|16,7
ANT-4s	16,8|16,7	AST-4s	14,8|15,4
ANT-5s	16,5|16,4	AST-5s	15,1|15,7
ANS-1s	13,0|13,2	ASS-1s	11,5|12,0
ANS-2s	13,5|12,4	ASS-2s	15,1|14,9
ANS-3s	12,9|14,0	ASS-3s	14,1|13,7
ANS-4s	13,1|15,0	ASS-4s	11,9|13,9
ANS-5s	12,3|10,9	ASS-5s	13,9|11,3

ANSs

NS-ISO 6891 (1991)

Table B2: Values for ANSs calculated from NS-ISO 6891 (1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
ANS1s	14,90	14,0	6,89	1,35	5,09
ANS2s	13,99	15,0	6,56	1,38	4,74
ANS3s	13,52	10,4	6,24	0,90	6,94
ANS4s	13,83	15,0	6,84	1,09	6,28
ANS5s*	–	–	–	–	–
Mean Values	14,06	13,6	6,63	1,18	5,76
Standard Deviations	0,59	2,17	0,30	0,23	1,03

* Specimen ANS5s was ruined during testing and is therefore not considered in the results.

NS-EN 12512 (2002)

Table B3: Values for ANSs calculated from NS-EN 12512 (2002). Yield point method is 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANS1s	15,66	15,17	30,0	8,99	1,57	5,72	19,08
ANS2s	14,51	13,80	30,0	8,11	1,42	5,71	21,11
ANS3s	13,52	12,89	30,0	6,88	0,85	8,11	35,36
ANS4s	14,05	13,14	30,0	8,00	1,02	7,86	29,47
ANS5s*	–	–	–	–	–	–	–
Mean Values	14,43	13,75	30,0	8,00	1,21	6,85	26,26
Standard Deviations	0,91	1,02	0,00	0,86	0,34	1,32	7,55

* Specimen ANS5s was ruined during testing and is therefore not considered in the results.

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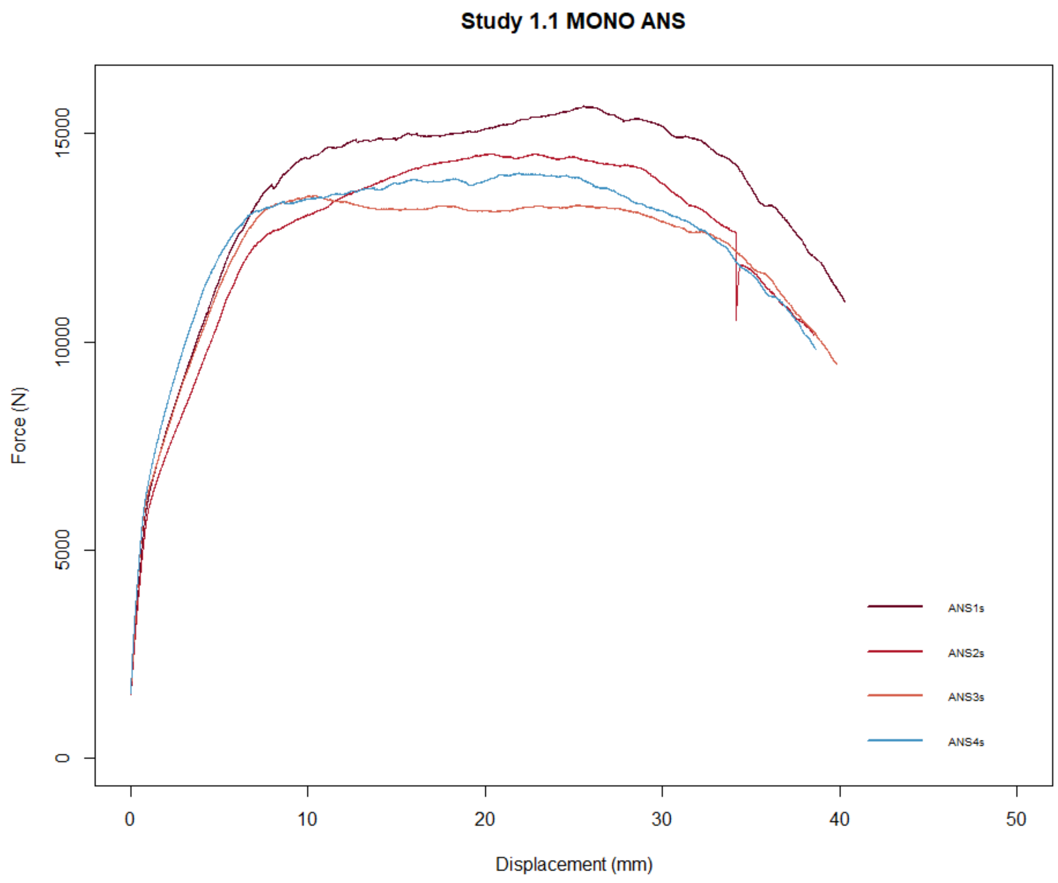
Table B4: Values for ANSs calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANS1s	15,66	15,66	15,17	30,0	14,22	2,68	4,72	11,19
ANS2s	14,51	14,51	13,80	30,0	13,19	2,52	4,60	11,88
ANS3s	13,52	13,52	12,89	30,0	12,63	1,77	6,24	16,96
ANS4s	14,05	14,05	13,14	30,0	13,14	1,84	6,26	16,32
ANS5s*	–	–	–	–	–	–	–	–
Mean Values	14,43	14,43	13,75	30,0	13,29	2,20	5,46	14,09
Standard Deviations	0,91	0,91	1,02	0,00	0,67	0,47	0,92	2,97



ANTs

NS-ISO 6891 (1991)

Table B5: Values for ANTs calculated from NS-ISO 6891 (1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
ANT1s	11,18	15,0	5,77	1,02	5,66
ANT2s	11,46	15,0	6,46	1,34	4,81
ANT3s	11,37	15,0	5,72	1,07	5,33
ANT4s	12,68	15,0	6,64	1,54	4,32
ANT5s	11,89	15,0	5,66	0,87	6,50
Mean Values	11,72	15,0	6,05	1,17	5,32
Standard Deviations	0,60	0,02	0,46	0,27	0,83

NS-EN 12512 (2002)

Table B6: Values for ANTs calculated from NS-EN 12512 (2002). Yield point method is 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANT1s	11,29	9,59	30,0	6,06	1,04	5,82	28,80
ANT2s	11,68	9,34	30,0	6,28	1,00	6,27	29,94
ANT3s	11,55	10,19	30,0	5,96	1,05	5,66	28,49
ANT4s	12,78	11,04	30,0	7,15	1,39	5,15	21,58
ANT5s	12,17	9,97	30,0	6,17	0,94	6,59	32,02
Mean Values	11,89	10,03	30,0	6,32	1,08	5,90	28,17
Standard Deviations	0,59	0,65	0,00	0,48	0,18	0,56	3,93

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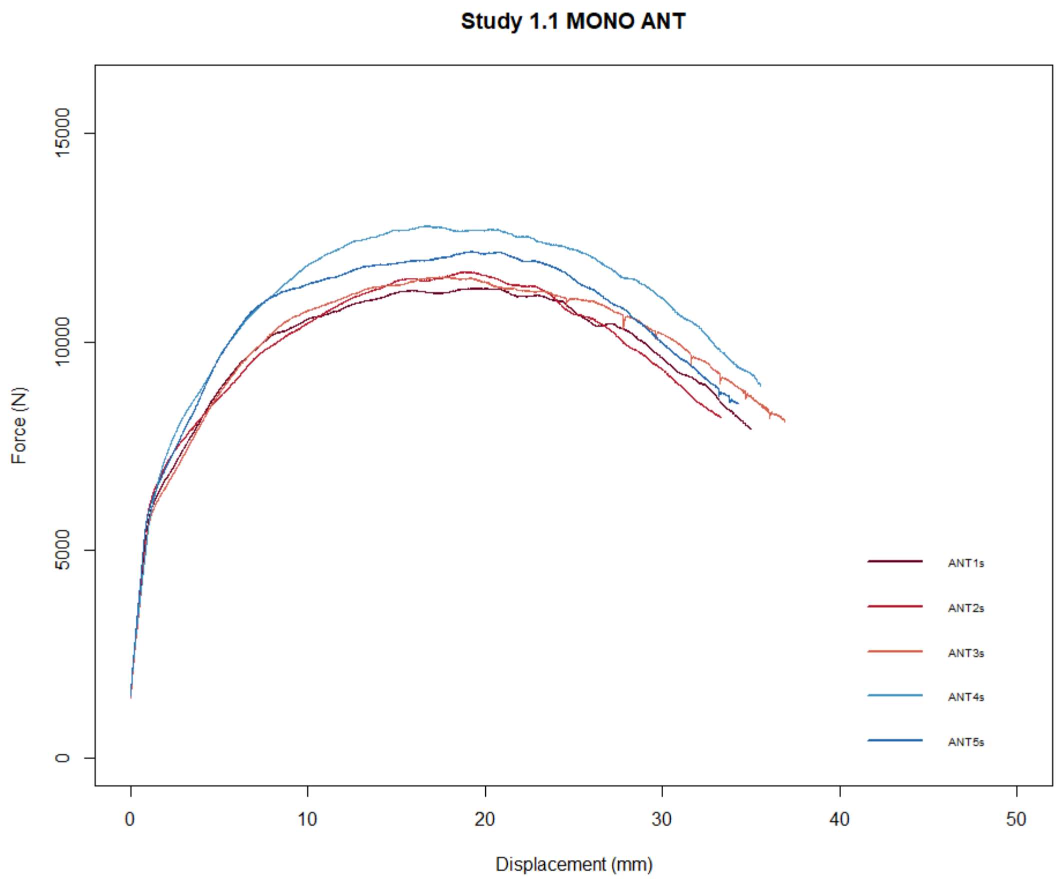
Table B7: Values for ANTs calculated from EN 12512 (2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANT1s	11,29	11,29	9,59	30,0	10,29	2,04	4,26	14,74
ANT2s	11,68	11,68	9,34	30,0	10,34	1,87	4,70	16,06
ANT3s	11,55	11,55	10,19	30,0	10,48	2,12	4,23	14,13
ANT4s	12,78	12,78	11,04	30,0	11,61	2,51	3,98	11,96
ANT5s	12,17	12,17	9,97	30,0	11,02	1,93	4,90	15,58
Mean Values	11,89	11,89	10,03	30,0	10,75	2,09	4,41	14,49
Standard Deviations	0,59	0,59	0,65	0,02	0,56	0,25	0,38	1,60



ASSs

NS-ISO 6891 (1991)

Table B8: Values for ASSs calculated from NS-ISO 6891 (1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
ASS1s	24,52	15,0	10,43	2,08	5,01
ASS2s	28,76	15,0	12,34	2,66	4,63
ASS3s	26,78	15,0	11,17	2,24	4,99
ASS4s	25,69	15,0	10,28	1,90	5,41
ASS5s	27,49	15,0	11,59	2,32	4,99
Mean Values	26,65	15,0	11,16	2,24	5,00
Standard Deviations	1,63	0,01	0,85	0,29	0,27

NS-EN 12512 (2002)

Table B9: Values for ASSs calculated from NS-EN 12512 (2002). Yield point method is 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ASS1s	25,92	20,74	27,5	17,61	3,90	4,51	7,05
ASS2s	30,97	27,54	30,0	23,36	5,75	4,06	5,22
ASS3s	27,66	22,38	30,0	19,86	4,41	4,50	6,80
ASS4s	25,89	20,71	28,7	18,29	3,91	4,68	7,34
ASS5s	28,16	22,53	26,0	20,03	4,28	4,68	6,07
Mean Values	27,72	22,78	28,4	19,83	4,45	4,49	6,49
Standard Deviations	2,08	2,80	1,72	2,22	0,76	0,25	0,85

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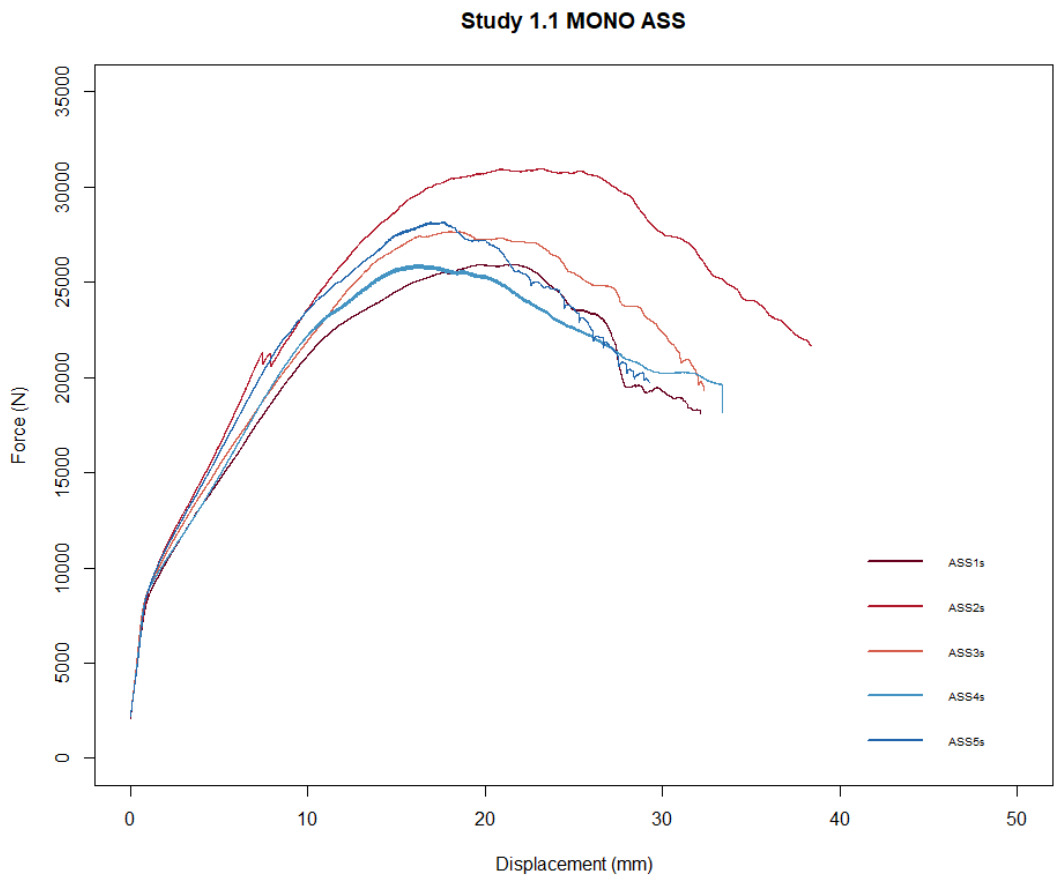
Table B10: Values for ASSs calculated from EN 12512 (2018) Draft proposal. Yield point method from EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ASS1s	25,92	25,92	20,74	27,5	22,57	5,18	3,90	5,32
ASS2s	30,97	30,97	27,54	30,0	27,67	6,95	3,59	4,32
ASS3s	27,66	27,66	22,38	30,0	24,10	5,49	3,93	5,46
ASS4s	25,89	25,89	20,71	28,7	22,46	4,93	4,07	5,81
ASS5s	28,16	28,16	22,53	26,0	24,25	5,31	4,10	4,89
Mean Values	27,72	27,72	22,78	28,4	24,21	5,57	3,92	5,16
Standard Deviations	2,08	2,08	2,80	1,72	2,10	0,80	0,20	0,58



ASTs

NS-ISO 6891 (1991)

Table B11: Values for ASTs calculated from NS-ISO 6891 (1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
AST1s	23,48	15,0	11,69	3,68	3,18
AST2s	25,19	15,0	10,44	1,88	5,57
AST3s	26,69	15,0	10,89	1,96	5,55
AST4s	23,72	15,0	9,90	1,57	6,30
AST5s	22,86	14,5	8,98	1,29	6,98
Mean Values	24,39	14,9	10,38	2,08	5,52
Standard Deviations	1,55	0,22	1,02	0,94	1,44

NS-EN 12512 (2002)

Table B12: Values for ASTs calculated from NS-EN 12512 (2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
AST1s	25,06	20,05	28,5	15,50	4,12	3,77	6,92
AST2s	25,86	23,89	30,0	16,78	3,27	5,13	9,17
AST3s	28,42	25,61	30,0	19,97	4,53	4,41	6,63
AST4s	24,01	19,21	29,6	14,39	2,32	6,20	12,76
AST5s	22,86	20,46	23,1	13,80	2,33	5,93	9,92
Mean Values	25,24	21,84	28,2	16,09	3,31	5,09	9,08
Standard Deviations	2,10	2,76	2,95	2,45	1,01	1,02	2,50

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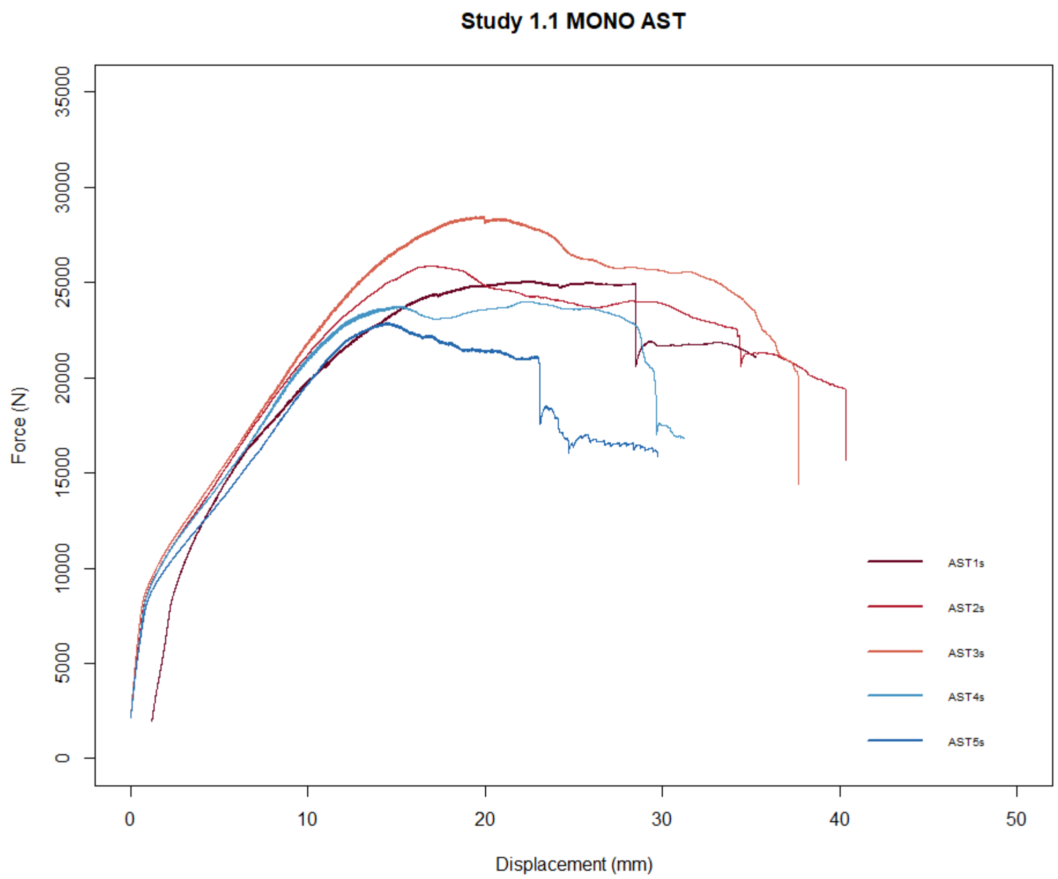
Table B13: Values for ASTs calculated from EN 12512 (2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
AST1s	25,06	25,06	24,79	28,4	22,31	5,60	4,58	5,08
AST2s	25,86	25,86	23,89	30,0	22,56	4,58	4,40	6,54
AST3s	28,42	28,42	25,61	30,0	24,68	5,76	3,83	5,21
AST4s	24,01	24,01	20,29	29,5	21,33	3,64	5,24	8,09
AST5s	22,86	22,86	21,10	23,0	19,33	3,44	4,97	6,70
Mean Values	25,24	25,24	23,14	28,2	22,04	4,60	4,60	6,32
Standard Deviations	2,10	2,10	2,33	2,95	1,95	1,07	0,54	1,24



HNSs

NS-ISO 6891 (1991)

Table B14: Values for HNSs calculated from NS-ISO 6891 (1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
HNS1s	11,51	15,0	5,14	0,64	7,99
HNS2s	11,96	15,0	6,29	0,99	6,33
HNS3s	10,26	15,0	6,01	0,74	8,14
HNS4s	10,69	15,0	5,96	0,86	6,94
HNS5s	10,64	15,0	6,20	1,19	5,23
Mean Values	11,01	15,0	5,92	0,88	6,93
Standard Deviations	0,70	0,01	0,46	0,21	1,21

NS-EN 12512 (2002)

Table B15: Values for HNSs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNS1s	11,91	11,20	20,9	5,51	0,69	7,93	30,04
HNS2s	13,00	12,96	30,0	5,97	0,68	8,75	43,99
HNS3s	11,26	11,22	30,0	5,65	0,52	10,94	58,02
HNS4s	11,48	11,19	30,0	5,68	0,64	8,94	47,20
HNS5s	12,01	11,90	30,0	6,01	0,92	6,53	32,58
Mean Values	11,93	11,70	28,2	5,76	0,69	8,62	42,37
Standard Deviations	0,67	0,77	4,08	0,22	0,15	1,61	11,39

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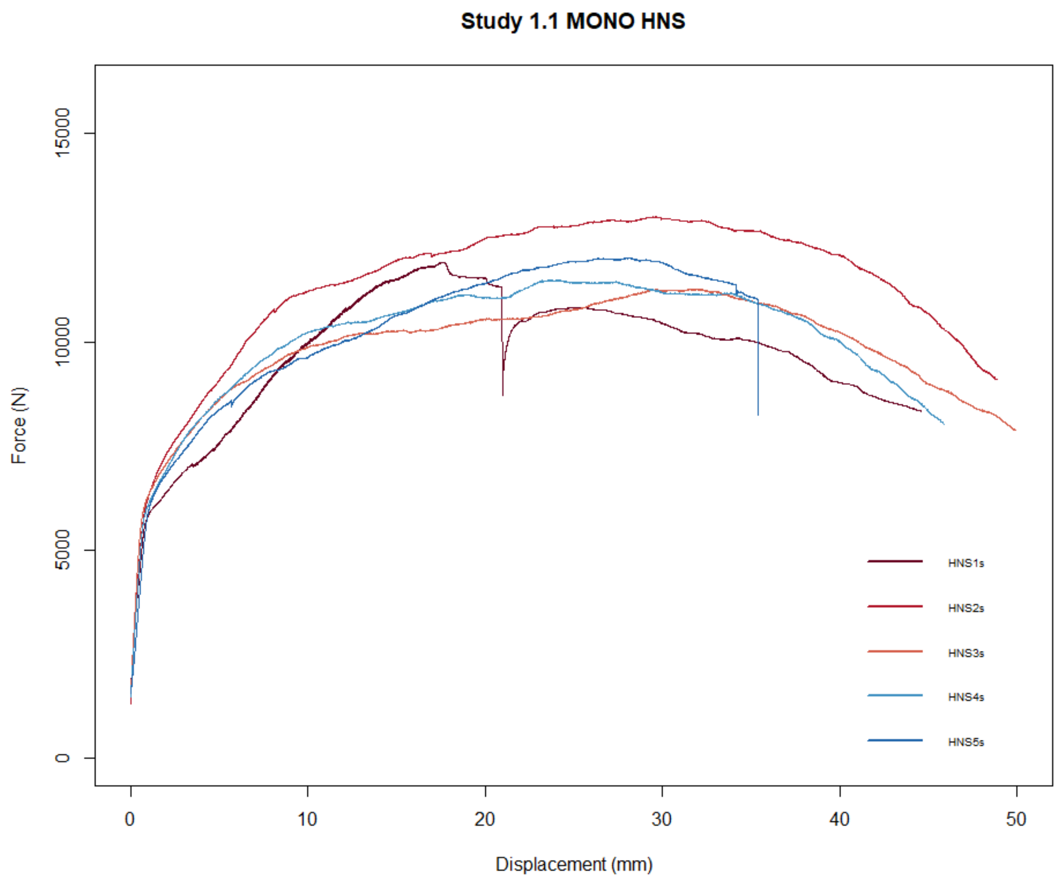
Table B16: Values for HNSs calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNS1s	11,91	11,91	11,20	20,9	9,78	1,47	5,53	14,28
HNS2s	13,00	13,00	12,96	30,0	11,39	1,49	6,69	20,10
HNS3s	11,26	11,25	11,22	30,0	9,89	1,05	7,90	28,49
HNS4s	11,48	11,48	11,19	30,0	10,28	1,34	6,55	22,43
HNS5s	12,01	12,01	11,90	30,0	10,36	1,82	4,83	16,48
Mean Values	11,93	11,93	11,70	28,2	10,34	1,43	6,30	20,35
Standard Deviations	0,67	0,67	0,77	4,05	0,64	0,28	1,17	5,53



HNTs

NS-ISO 6891 (1991)

Table B17: Values for HNTs calculated from NS-ISO 6891(1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
HNT1s	12,41	15,0	6,52	1,02	6,38
HNT2s	12,09	15,0	6,91	1,32	5,23
HNT3s	10,64	15,0	6,35	1,15	5,53
HNT4s	11,05	15,0	6,02	1,12	5,36
HNT5s	10,81	15,0	6,52	1,61	4,06
Mean Values	11,40	15,0	6,46	1,24	5,31
Standard Deviations	0,80	0,00	0,32	0,23	0,83

NS-EN 12512 (2002)

Table B18: Values for HNTs calculated from NS-EN 12512 (2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNT1s	13,32	12,83	30,0	6,45	0,79	8,19	38,05
HNT2s	13,11	12,62	27,4	6,69	0,92	7,24	29,66
HNT3s	11,68	11,23	30,0	6,67	1,01	6,60	29,68
HNT4s	12,66	12,45	30,0	6,03	0,99	6,07	30,22
HNT5s	11,96	11,68	30,0	6,69	1,30	5,14	23,04
Mean Values	12,54	12,16	29,5	6,51	1,00	6,65	30,13
Standard Deviations	0,71	0,68	1,15	0,29	0,19	1,15	5,32

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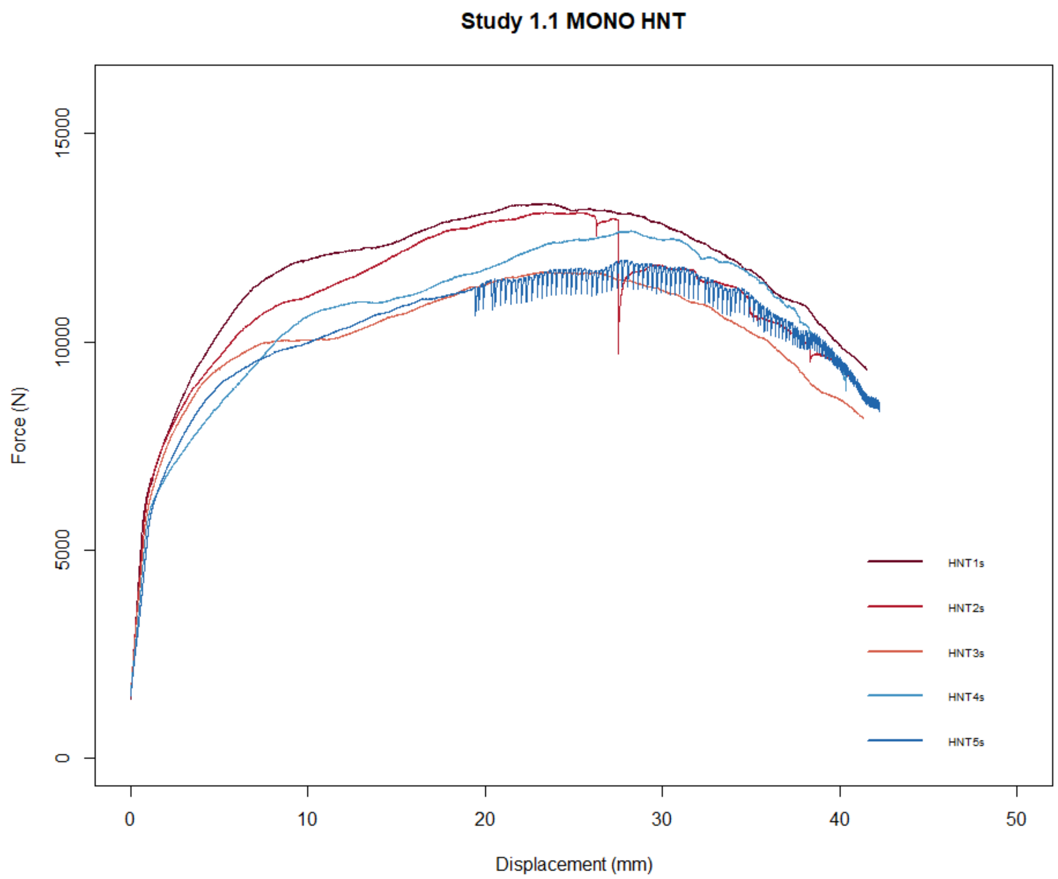
Table B19: Values for HNTs calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNT1s	13,32	13,32	12,83	30,0	12,03	1,67	6,32	17,96
HNT2s	13,11	13,11	12,79	27,5	11,55	1,80	5,54	15,26
HNT3s	11,68	11,68	11,23	30,0	10,52	1,78	5,01	16,87
HNT4s	12,66	12,66	12,45	30,0	10,86	2,07	4,47	14,48
HNT5s	11,96	11,96	11,68	30,0	10,50	2,27	3,96	13,23
Mean Values	12,54	12,54	12,20	29,5	11,09	1,92	5,06	15,56
Standard Deviations	0,71	0,71	0,71	1,12	0,67	0,25	0,92	1,88



HSSs

NS-ISO 6891 (1991)

Table B20: Values for HSSs calculated from NS-ISO 6891(1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
HSS1s	19,97	14,9	8,85	0,99	8,93
HSS2s	21,33	15,0	10,47	1,34	7,80
HSS3s	18,91	15,0	10,67	1,41	7,55
HSS4s	20,45	14,4	10,65	1,70	6,25
HSS5s	18,31	14,5	8,53	1,02	8,33
Mean Values	19,79	14,8	9,83	1,29	7,77
Standard Deviations	1,21	0,28	1,05	0,30	1,00

NS-EN 12512 (2002)

Table B21: Values for HSSs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HSS1s	20,55	20,44	30,0	9,15	0,88	10,41	34,12
HSS2s	23,16	23,05	30,0	10,95	1,13	9,66	26,47
HSS3s	20,81	20,63	30,0	10,67	0,93	11,46	32,24
HSS4s	21,53	21,50	30,0	10,40	1,07	9,73	28,06
HSS5s	19,41	19,32	30,0	8,25	0,79	10,48	38,12
Mean Values	21,09	20,99	30,0	9,88	0,96	10,35	31,80
Standard Deviations	1,39	1,39	0,00	1,14	0,14	0,73	4,69

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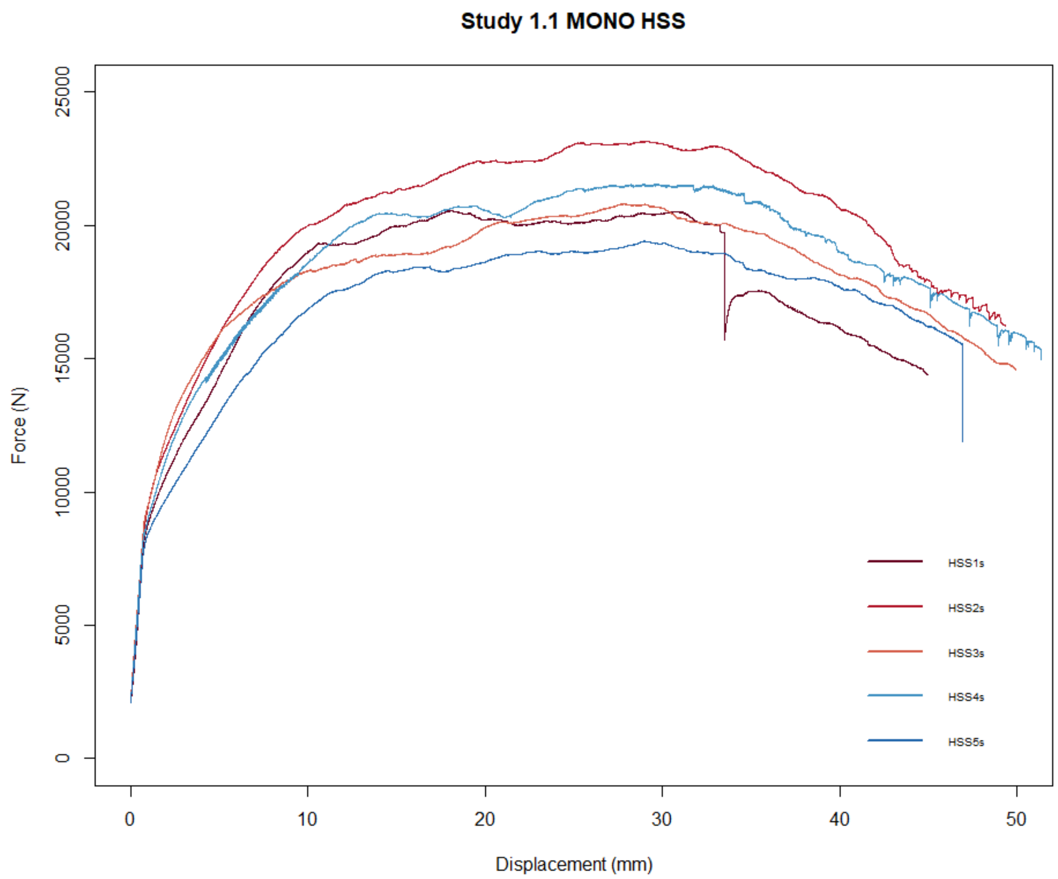
Table B22: Values for HSSs calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HSS1s	20,55	20,55	20,44	30,0	18,53	2,04	8,04	14,67
HSS2s	23,16	23,16	23,05	30,0	20,40	2,35	7,76	12,76
HSS3s	20,81	20,81	20,63	30,0	18,48	1,79	9,09	16,76
HSS4s	21,53	21,53	21,50	30,0	19,07	2,19	7,71	13,67
HSS5s	19,41	19,41	19,32	30,0	16,99	1,91	7,76	15,68
Mean Values	21,09	21,09	20,99	30,0	18,70	2,06	8,07	14,71
Standard Deviations	1,39	1,39	1,39	0,00	1,23	0,22	0,58	1,58



HST

NS-ISO 6891 (1991)

Table B23: Values for HST calculated from NS-ISO 6891(1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
HST1s	25,68	15,0	12,40	2,55	4,86
HST2s	28,37	15,0	13,73	1,92	7,14
HST3s	23,37	11,0	13,08	1,59	8,21
HST4s	26,81	15,0	12,99	1,46	8,92
HST5s	27,37	15,0	12,97	1,60	8,12
Mean Values	26,32	14,2	13,03	1,82	7,45
Standard Deviations	1,91	1,79	0,47	0,44	1,58

NS-EN 12512 (2002)

Table B24: Values for HST calculated from NS-EN 12512 (2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HST1s	29,48	28,15	30,0	17,89	3,70	4,84	8,11
HST2s	29,53	28,56	30,0	14,11	1,37	10,28	21,85
HST3s	24,82	22,73	11,0	11,97	0,93	12,82	11,74
HST4s	30,04	30,02	30,0	12,80	1,12	11,40	26,72
HST5s	32,69	31,04	30,0	15,52	2,08	7,46	14,41
Mean Values	29,31	28,10	26,2	14,46	1,84	9,36	16,57
Standard Deviations	2,84	3,21	8,51	2,34	1,13	3,20	7,59

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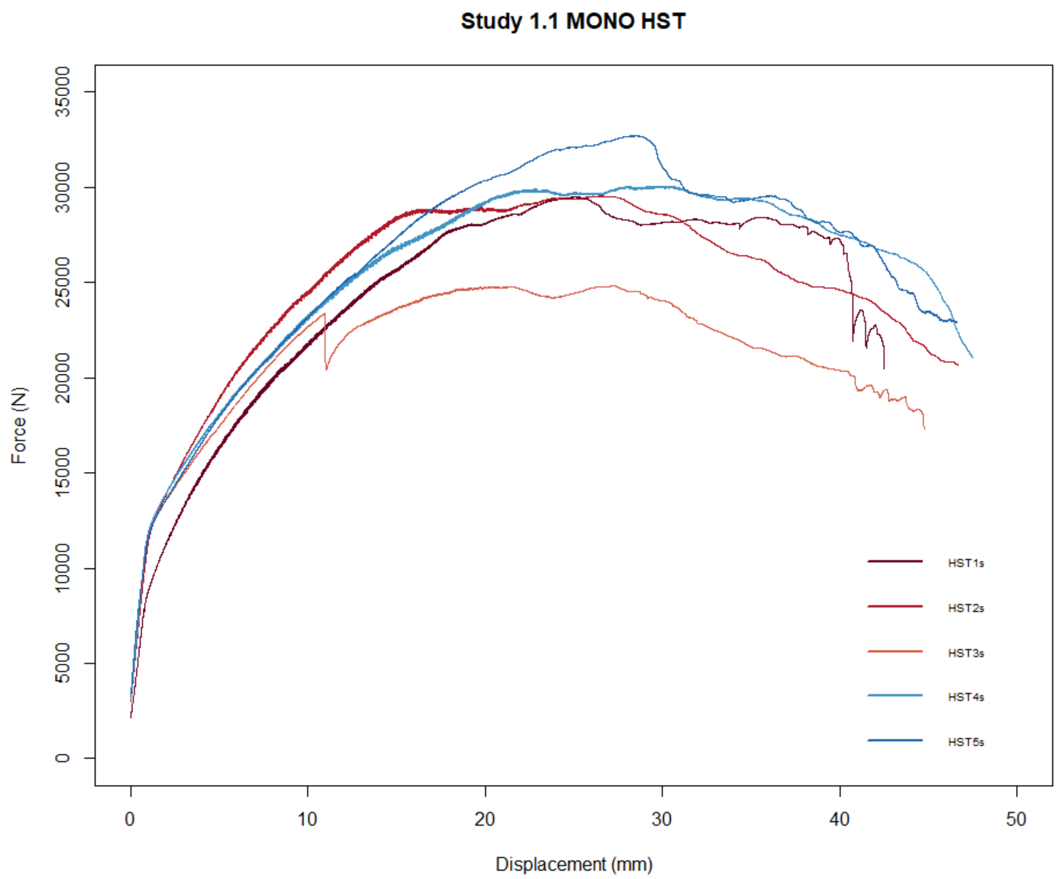
Table B25: Values for HST calculated from EN 12512 (2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HST1s	29,48	29,48	28,15	30,0	25,29	5,48	4,16	5,48
HST2s	29,53	29,53	28,56	30,0	26,00	2,85	8,04	10,52
HST3s	24,82	23,37	23,40	11,0	18,50	1,60	9,57	6,86
HST4s	30,04	30,04	30,02	30,0	25,49	2,60	8,62	11,56
HST5s	32,69	32,69	31,04	30,0	26,97	4,05	5,82	7,41
Mean Values	29,31	29,02	28,23	26,2	24,45	3,31	7,24	8,37
Standard Deviations	2,84	3,42	2,94	8,51	3,39	1,49	2,21	2,57



Appendix C – Study 1.2 (Cyclic Load Test)

Moisture Content

Moisture content measured with moisturemeter for every specimen in each test group for study 1.2.

Table C1: Moisture content for specimens in study 1.2

specimen	moisture content % sill1|sill2|TW	specimen	moisture content % sill1|sill2|TW
HST-1s	16,1|16,0|13,1	HNS-1s	14,3|14,6|12,7
HST-2s	16,7|16,6|12,0	HNS-2s	14,1|12,5|13,4
HST-3s	15,6|15,2|11,7	HNS-3s	13,6|12,8|13,0
HST-4s	16,4|15,0|12,2	HNS-4s	13,1|12,1|12,5
HST-5s	12,9|12,9|11,5	HNS-5s	11,7|13,2|12,0
HSS-1s	12,9|12,0|11,4	HNT-1s	15,8|15,2|11,6
HSS-2s	14,2|14,1|12,0	HNT-2s	16,2|16,7|12,9
HSS-3s	14,4|14,8|12,9	HNT-3s	16,3|16,8|12,8
HSS-4s	12,5|11,9|12,2	HNT-4s	15,2|15,3|11,9
HSS-5s	14,5|14,8|12,9	HNT-5s	13,1|12,9|11,6
ANT-1s	14,6|14,9|11,4	AST-1s	15,9|15,7|11,8
ANT-2s	16,1|16,3|12.0	AST-2s	16,1|16,3|12,9
ANT-3s	16,7|16,6|13,6	AST-3s	16,3|16,1|11,8
ANT-4s	15,8|16,0|12,9	AST-4s	15,6|15,0|11,6
ANT-5s	15,5|16,8|13,2	AST-5s	13,8|12,6|10,9
ANS-1s	12,4|11,7|11,5	ASS-1s	12,5|11,8|13,4
ANS-2s	11,7|14,4|12,2	ASS-2s	12,6|15,2|12,0
ANS-3s	15,2|14,9|13,1	ASS-3s	13,5|13,0|14,0
ANS-4s	14,1|15,7|12,1	ASS-4s	13,3|11,9|12,1
ANS-5s	15,7|13,0|11,8	ASS-5s	12,4|12,7|11,5

ANSc

NS-EN 12512 (2002)

Table C2: Values for ANSc calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

Tension/ compression	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ANS1c	10,17/-13,77	8,14/-11,02	13,4/-13,1	6,77	2,6	2,59	5,13
ANS2c	8,77/-12,67	7,01/-10,14	14,2/-13,8	7,42	4,6	1,60	3,06
ANS3c	8,47/-12,62	6,78/-10,09	14,2/-14,8	6,19	3,0	2,08	4,76
ANS4c	8,63/-12,43	6,90/-9,95	13,8/-14,8	6,98	5,6	1,24	2,45
ANS5c*	–	–	–	–	–	–	–
Mean Values	9,01/-12,87	7,21/-10,30	13,9/-14,1	6,84	4,0	1,88	3,85
Standard Deviations	0,78/0,61	0,63/0,49	0,4/0,8	0,51	1,4	0,59	1,30

* Specimen ANS5c was ruined during testing and is therefore not considered in the results.

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Table C3: Values for ANSc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ANS1c	10,23/-13,96	9,55/-12,35	9,55/-12,35	9,9/-8,9	7,71/-9,51	2,7/-2,0	2,57/4,27	3,63/4,41
ANS2c	8,87/-12,80	8,12/-11,86	8,13/-11,86	10,3/-8,4	6,60/-9,52	3,8/-1,9	1,61/4,63	2,74/4,45
ANS3c	8,58/-12,81	8,51/-11,49	8,51/-11,49	11,6/-8,5	7,09/-9,04	3,4/-1,7	1,89/4,68	3,42/5,02
ANS4c	8,74/12,63	5,48/-11,03	5,48/-11,03	5,0/-9,5	4,62/-8,76	2,9/-3,2	1,46/2,80	1,74/2,97
ANS5c*	–	–	–	–	–	–	–	–
Mean Values	9,10/-13,05	7,91/-11,68	7,92/-11,68	9,2/-8,8	6,50/-9,21	3,2/-2,2	1,88/4,10	2,88/4,21
Standard Deviations	0,76/0,61	1,73/0,56	1,74/0,56	2,91/0,51	1,33/0,38	0,48/0,69	0,49/0,88	0,85/0,88

* Specimen ANS5c was ruined during testing and is therefore not considered in the results.

Cyclic load-displacement curve

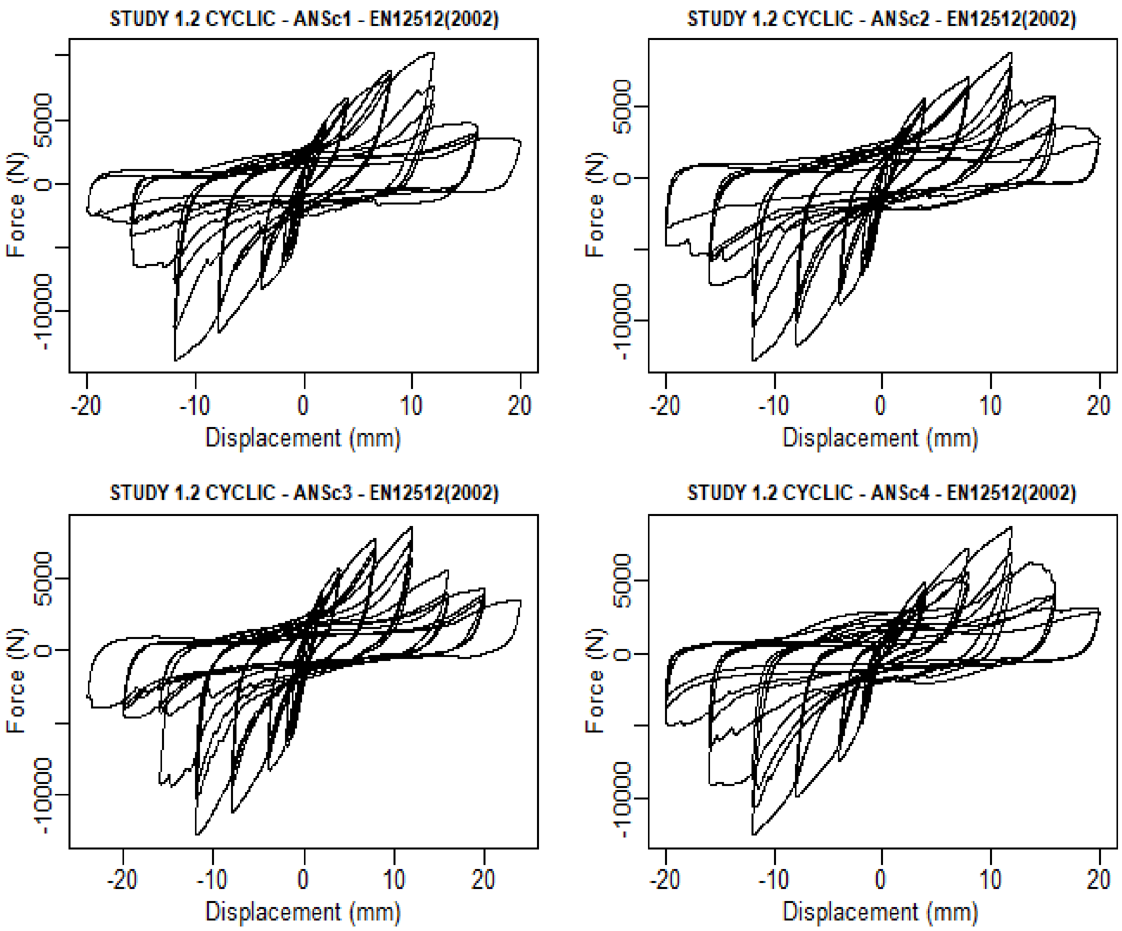

Figure C1: Cyclic load-displacement curves for each specimen in test group ANSc.

ANTc

NS-EN 12512 (2002)

Table C4: Values for ANTc from NS-EN 12512 (2002). Yield point method is the 1/6 procedure

Tension/ compression	Maximum Force (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ANT1c	7,67/-10,33	6,14/-8,27	14,9/-13,8	7,07	7,0	1,01	2,13
ANT2c	8,17/-13,55	6,53/-10,84	13,8/-13,5	6,40	7,0	0,91	1,97
ANT3c	9,01/-11,62	7,21/-9,30	13,5/-13,2	3,86	1,2	3,18	11,11
ANT4c	8,31/-10,97	6,65/-8,78	13,0/-13,5	5,73	2,1	2,77	6,26
ANT5c	8,12/-11,65	6,50/-9,32	12,9/-13,4	6,07	2,4	2,57	5,47
Mean Values	8,26/-11,63	6,60/-9,30	13,6/-13,5	5,83	3,9	2,09	5,39
Standard Deviations	0,48/1,20	0,39/0,96	0,8/0,2	1,21	2,8	1,05	3,74

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Table C5: Values for ANTc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ANT1c	7,78/-10,54	7,48/-9,80	7,48/-9,81	10,9/-9,91	6,41/-7,95	5,96/-1/,47	1,04/4,85	1,83/6,75
ANT2c	8,26/-13,87	6,47/-12,42	6,47/-12,42	9,45/-8,92	5,01/-9,74	5,35/-0,51	1,06/18,05	1,77/17,38
ANT3c	9,10/-11,83	7,51/-10,61	7,51/-10,61	9,03/-8,87	5,82/-8,75	1,40/-2,40	3,70/3,44	6,44/3,69
ANT4c	8,41/-11,89	8,41/-11,38	8,19/-11,38	9,65/-9,04	7,07/-9,80	2,6/-4,82	2,49/1,99	3,71/1,87
ANT5c	8,27/-12,68	8,24/-11,10	8,24/-11,10	9,56/-9,08	7,07/-9,04	2,77/-3,57	2,3/2,31	3,45/2,54
Mean Values	8,36/-12,16	7,62/-11,06	7,58/11,06	9,72/-9,16	6,27/-9,05	3,62/-2,56	2,12/6,13	3,44/6,45
Standard Deviations	0,48/1,22	0,77/0,97	0,72/0,96	0,70/0,43	0,88/0,76	1,95/1,70	1,11/6,76	1,90/6,39

Cyclic load-displacement curve

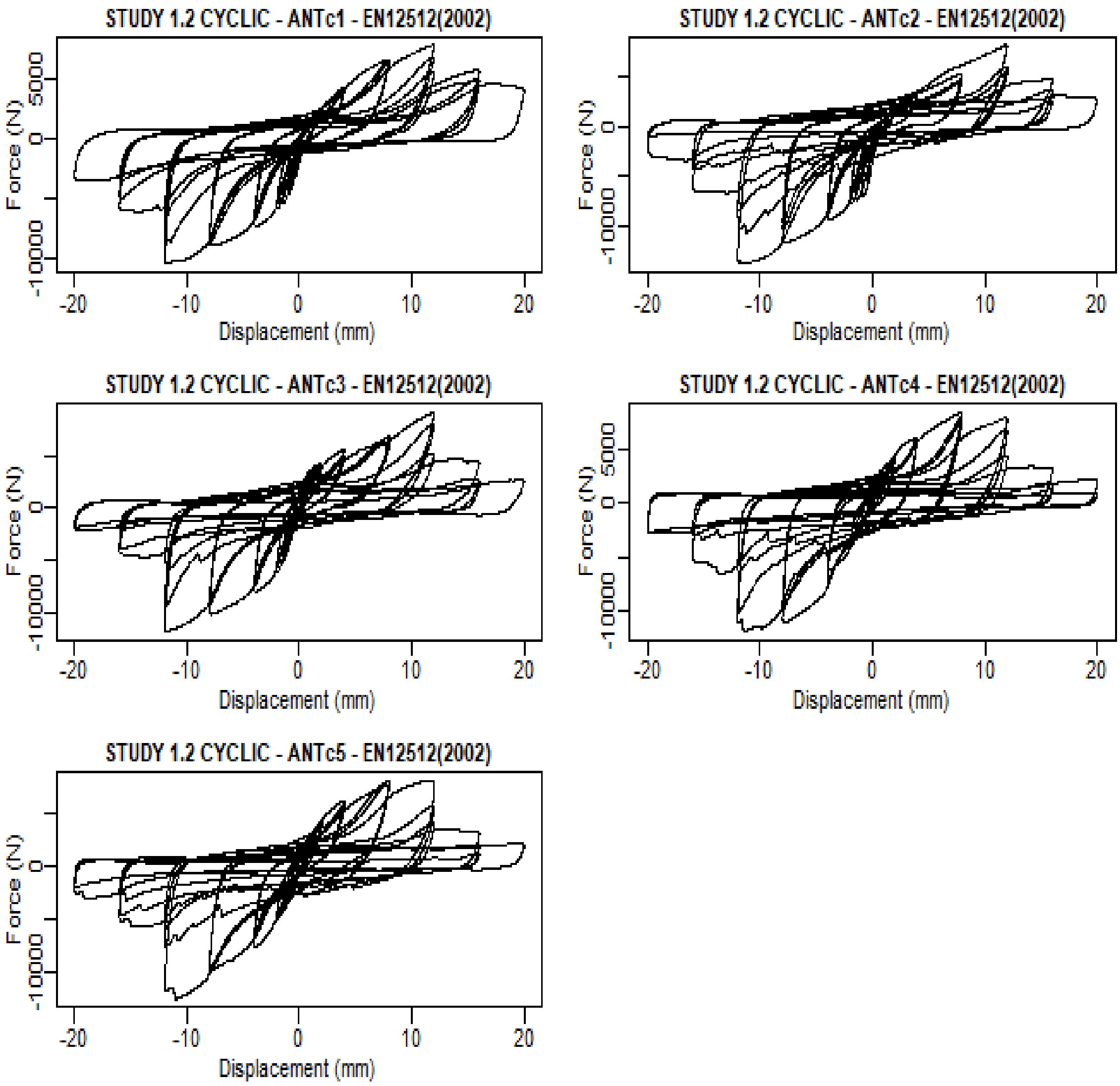

Figure C2: Cyclic load-displacement curves for each specimen in test group ANTc.

ASSc

NS-EN 12512 (2002)

Table C6: Values for ASSc from NS-EN 12512 (2002). Yield point method is the 1/6 procedure

Tension/ compression	Maximum Force (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ASS1c	18,49/-27,33	14,80/-21,86	21,9/-20,9	16,89	9,2	1,84	2,39
ASS2c	20,63/-26,88	16,50/-21,50	21,9/-21,6	11,15	1,9	5,80	11,38
ASS3c	17,99/-32,46	14,40/-25,97	19,5/-18,4	14,16	5,5	2,59	3,56
ASS4c	18,47/-28,36	14,78/-22,69	21,3/-21,2	16,15	7,9	2,03	2,68
ASS5c	21,40/-37,92	17,12/-30,34	20,5/-20,0	18,11	7,4	2,45	2,77
Mean Values	19,40/-30,59	15,52/-24,47	21,0/-20,4	15,29	6,4	2,94	4,56
Standard Deviations	1,51/4,65	1,21/3,72	1,0/1,3	2,72	2,8	1,62	3,84

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Table C7: Values for ASSc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
ASS1c	18,62/-27,43	18,62/-27,43	18,33/-25,16	17,6/-19,1	17,27/-23,36	9,27/-9,26	1,65/2,29	1,90/2,07
ASS2c	20,73/-26,97	20,73/-17,19	20,70/-17,19	17,7/-6,7	16,91/-12,87	3,17/-2,53	4,57/5,03	5,59/2,66
ASS3c	20,31/-32,54	20,31/-32,54	16,25/-29,66	17,5/-17,1	18,08/-29,36	6,92/-9,58	2,34/2,84	2,53/1,78
ASS4c	18,58/-28,45	18,58/-28,45	17,13/-27,75	19,7/-17,2	16,29/-23,65	7,86/-5,75	1,87/3,71	2,50/2,99
ASS5c	21,46/-38,00	21,46/-38,00	20,21/-35,48	17,7/-17,4	19,15/-32,36	7,67/-7,41	2,47/3,95	2,31/2,34
Mean Values	19,94/-30,68	19,94/-28,72	18,53/-27,05	18,0/-15,5	17,54/-24,32	6,98/-6,91	2,58/3,56	2,96/2,37
Standard Deviations	1,29/4,65	1,29/7,67	1,92/6,69	0,91/4,98	1,11/7,46	2,29/2,89	1,16/1,06	1,49/0,48

Cyclic load-displacement curve

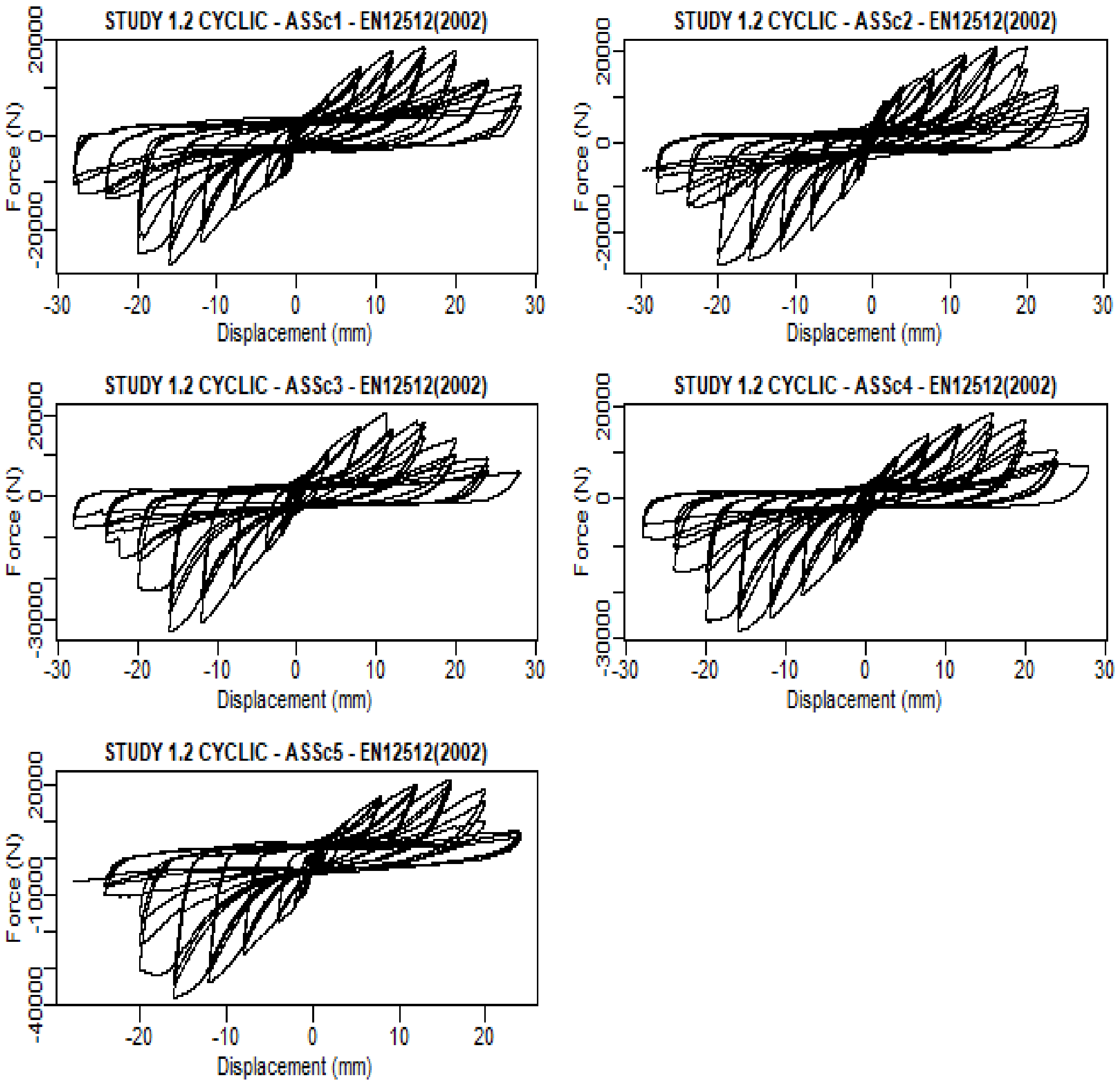

Figure C3: Cyclic load-displacement curves for each specimen in test group ASSc.

ASTc

NS-EN 12512 (2002)

Table C8: Values for ASTc from NS-EN 12512 (2002). Yield point method is the 1/6 procedure

Tension/ compression	Maximum Force (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
AST1c	15,11/-18,31	12,09/-14,65	20,3/-21,4	13,35	5,8	2,32	3,53
AST2c	17,10/-23,87	13,68/-19,10	17,6/-17,6	15,08	6,6	2,27	2,65
AST3c	17,75/-27,68	14,20/-22,15	17,8/-17,8	14,68	5,3	2,76	3,36
AST4c	18,73/-20,61	14,98/-16,49	16,5/-19,3	15,00	5,0	3,03	3,34
AST5c	18,93/-25,25	15,15/-20,20	15,1/-17,6	15,48	4,8	3,22	3,14
Mean Values	17,53/-23,15	14,02/-18,52	17,5/-18,7	14,72	5,5	2,72	3,21
Standard Deviations	1,54/3,72	1,23/2,97	1,9/1,6	0,82	0,7	0,42	0,34

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Table C9: Values for ASTc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
AST1c	15,23/-18,47	15,23/-18,47	13,51/-18,36	16,7/-17,0	13,75/-15,82	5,79/-6,24	2,09/2,77	2,88/2,72
AST2c	17,19/-24,02	16,94/-21,22	16,94/-21,22	13,7/-12,5	14,75/-16,70	6,24/-5,32	2,13/3,14	2,19/2,35
AST3c	17,84/-27,85	17,70/-26,44	17,70/-26,45	14,0/-13,2	15,38/-21,58	5,45/-7,02	2,49/2,91	2,56/1,87
AST4c	18,84/-20,83	18,84/-20,15	15,07/-20,15	16,5/-12,3	16,37/-16,00	6,10/-5,51	2,30/2,99	2,70/2,22
AST5c	18,99/-26,23	18,99/-25,32	15,84/-25,33	14,6/-12,2	15,88/-19,83	4,82/-6,05	2,91/3,20	3,02/2,01
Mean Values	17,62/-23,48	17,54/-22,32	15,81/-22,30	15,1/-13,4	15,22/-17,99	5,68/-6,03	2,39/3,00	2,67/2,24
Standard Deviations	1,53/3,84	1,54/3,42	1,63/3,45	1,41/2,03	1,02/2,58	0,57/0,67	0,34/0,17	0,32/0,33

Cyclic load-displacement curve

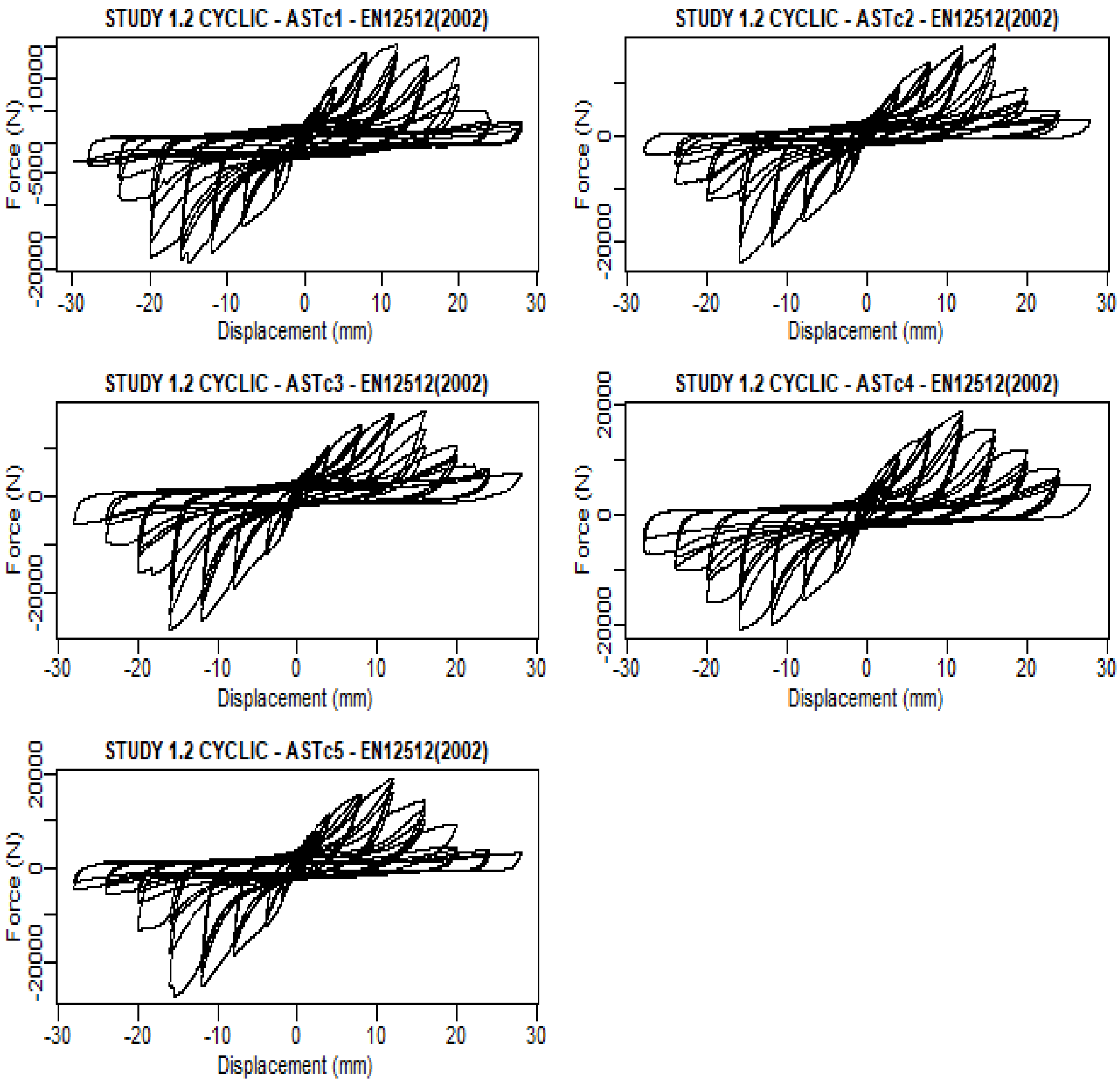

Figure C4: Cyclic load-displacement curves for each specimen in test group ASTc.

HNSc

NS-EN 12512 (2002)

Table C10: Values for HNSc from NS-EN 12512 (2002). Yield point method is the 1/6 procedure

Tension/ compression	Maximum Force (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HNS1c	8,84/-11,17	7,07/-8,94	14,9/-15,1	4,66	1,6	2,90	9,25
HNS2c	7,81/-9,96	6,25/-7,96	15,2/-15,4	5,80	4,2	1,38	3,63
HNS3c	8,18/-12,55	6,55/-10,04	15,9/-14,8	3,39	0,6	5,65	26,43
HNS4c	7,81/-10,68	6,25/-8,54	14,8/-16,1	5,99	5,6	1,07	2,66
HNS5c	7,45/-10,37	5,96/-8,30	15,2/-13,9	4,12	2,0	2,08	7,69
Mean Values	8,02/-10,95	6,41/-8,76	15,2/-15,1	4,79	2,8	2,62	9,93
Standard Deviations	0,53/1,00	0,42/0,80	0,4/0,8	1,11	2,0	1,83	9,62

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Table C11: Values for HNSc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HNS1c	8,89/-11,24	8,89/-11,24	7,11/-8,99	14,9/-15,1	7,12/-9,40	2,64/-3,05	2,41/2,79	5,64/4,96
HNS2c	7,86/-10,04	7,64/-9,73	7,64/-9,73	11,1/-11,1	6,22/-7,71	3,82/-2,31	1,50/3,05	2,90/4,81
HNS3c	8,22/-12,63	8,22/-11,14	7,92/-11,16	12,7/-10,1	6,43/-8,64	1,04/-3,49	5,62/2,41	12,23/2,91
HNS4c	7,86/-10,76	7,86/-10,76	6,29/-8,93	14,8/-15,5	6,50/-8,60	5,94/-2,07	0,97/3,83	2,50/7,51
HNS5c	7,49/-10,45	7,49/-10,45	6,00/-8,36	15,2/-13,9	5,98/-8,63	3,00/-2,79	1,73/2,93	5,07/4,97
Mean Values	8,07/-11,02	8,02/-10,66	6,99/-9,43	13,7/-13,1	6,45/-8,59	3,29/-2,74	2,45/3,00	5,67/5,03
Standard Deviations	0,53/1,00	0,56/0,61	0,83/1,08	1,79/2,41	0,43/0,60	1,79/0,57	1,85/0,52	3,91/1,64

Cyclic load-displacement curve

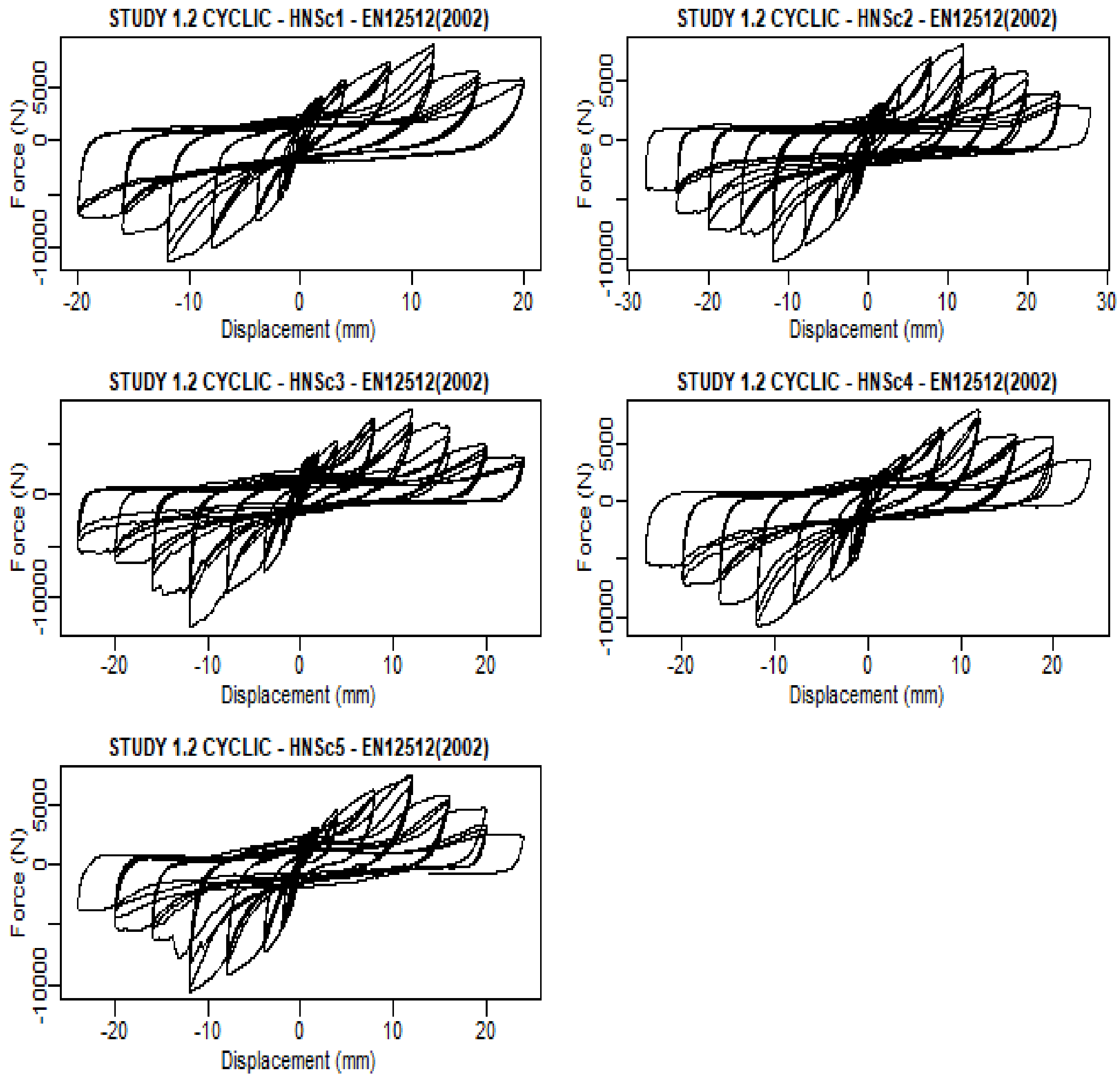

Figure C5: Cyclic load-displacement curves for each specimen in test group HNSc.

HNTc

NS-EN 12512 (2002)

Table C12: Values for HNTc from NS-EN 12512 (2002). Yield point method is the 1/6 procedure

Tension/ compression	Maximum Force (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HNT1c	8,26/-11,85	6,61/-9,48	13,8/-13,9	5,09	2,1	2,47	6,70
HNT2c	7,99/-12,10	6,39/-9,68	14,5/-13,9	7,21	5,6	1,29	2,60
HNT3c	8,94/-12,93	7,15/-10,34	13,6/-13,0	8,18	5,2	1,57	2,61
HNT4c	7,48/-11,73	5,98/-9,39	12,6/-13,6	7,39	4,5	1,63	2,77
HNT5c	9,47/-12,16	7,57/-9,73	13,5/-13,4	8,23	6,1	1,35	2,22
Mean Values	8,43/-12,15	6,74/-9,72	13,6/-13,5	7,22	4,7	1,66	3,38
Standard Deviations	0,79/0,47	0,63/0,37	0,7/0,4	1,28	1,6	0,47	1,87

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Table C13: Values for HNTc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HNT1c	8,44/-12,25	7,69/-10,32	7,69/-10,33	8,8/-8,3	6,13/-8,47	2,36/-2,09	2,28/3,72	3,72/3,95
HNT2c	8,12/-13,02	7,99/-12,88	8,00/-12,88	10,9/-9,7	7,30/-10,59	5,31/-1,01	1,28/9,34	2,05/9,51
HNT3c	9,07/-13,31	8,85/-13,31	8,85/-12,94	9,9/-8,9	7,98/-10,92	4,79/-2,19	1,50/4,47	2,05/4,06
HNT4c	7,59/-11,86	7,59/-11,72	7,59/-11,72	9,6/-9,5	6,62/-9,72	3,90/-1,99	1,54/4,50	2,46/4,77
HNT5c	9,59/-12,50	9,00/-11,52	9,00/-11,52	9,1/-9,5	7,55/-9,57	5,24/-4,42	1,25/2,02	1,74/2,14
Mean Values	8,56/-12,59	8,23/-11,95	8,23/-11,88	9,7/-9,2	7,12/-9,85	4,32/-2,34	1,57/4,81	2,41/4,89
Standard Deviations	0,78/0,58	0,66/1,19	0,66/1,08	0,80/0,57	0,74/-0,96	4,32/-2,34	0,42/2,72	0,78/2,76

Cyclic load-displacement curve

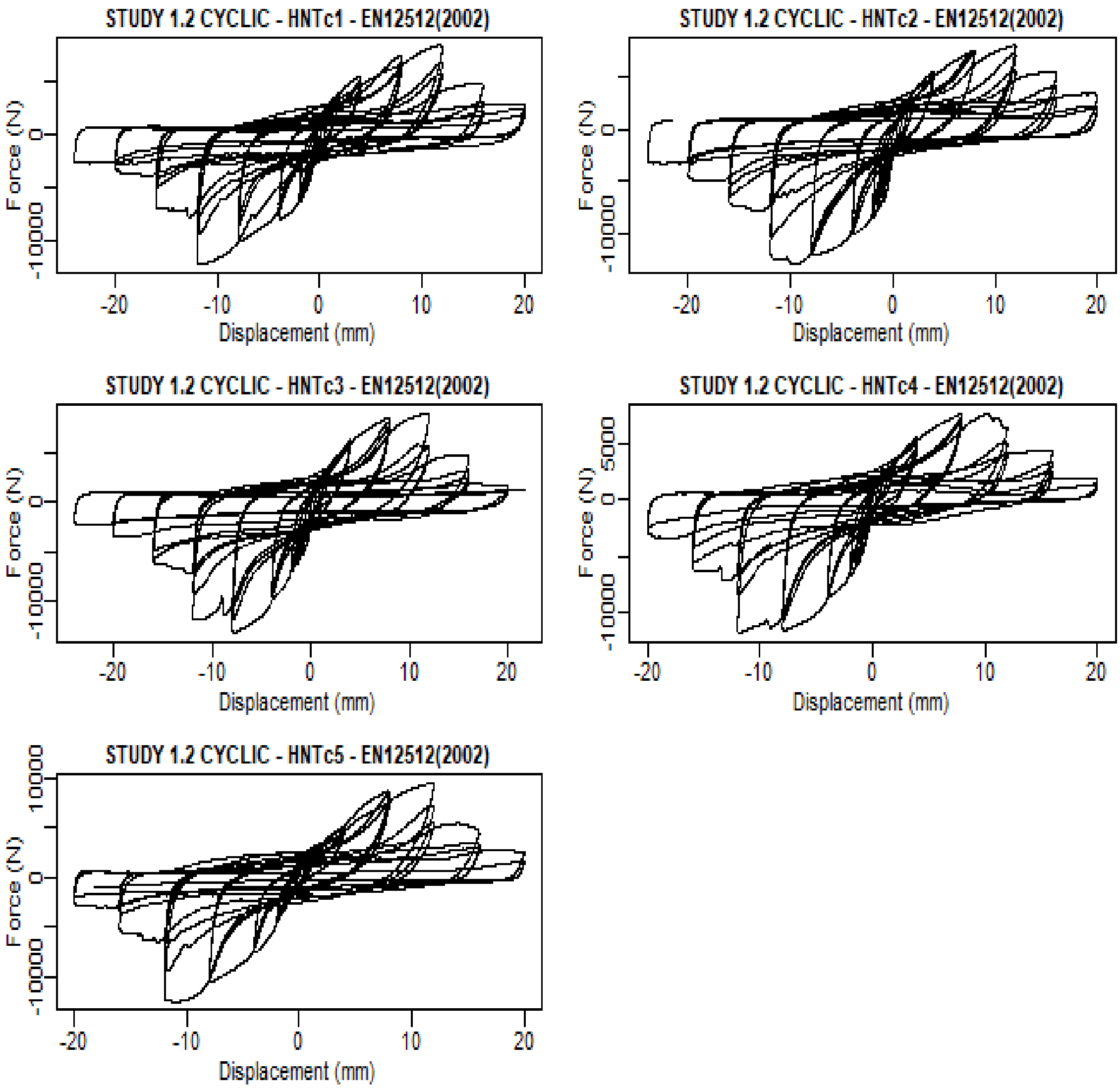

Figure C6: Cyclic load-displacement curves for each specimen in test group HNTc.

HSSc

NS-EN 12512 (2002)

Table C14: Values for HSSc from NS-EN 12512 (2002). Yield point method is the 1/6 procedure

Tension/ compression	Maximum Force (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HSS1c	14,37/-20,43	11,50/-16,34	21,7/-21,4	9,52	2,21	4,31	9,83
HSS2c	15,41/-24,82	12,33/-19,86	21,5/-20,7	13,30	6,10	2,18	3,52
HSS3c	15,76/-20,74	12,61/-16,59	24,5/-22,8	12,00	4,69	2,56	5,24
HSS4c	14,35/-21,20	11,48/-16,96	22,0/-21,8	10,42	4,47	2,33	4,92
HSS5c	15,16/-25,97	12,13/-20,78	19,1/-18,1	12,34	5,20	2,37	3,67
Mean Values	15,01/-22,63	12,01/-18,11	21,8/-20,9	11,52	4,53	2,75	5,43
Standard Deviations	0,63/2,57	0,50/2,06	1,94/1,76	1,52	1,44	0,88	2,57

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Table C15: Values for HSSc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HSS1c	14,56/-20,61	14,56/-20,61	13,89/-20,01	18,1/-16,5	12,76/-18,34	2,88/-7,11	3,90/2,58	6,29/2,33
HSS2c	15,47/-25,08	15,47/-24,84	13,74/-24,84	19,6/-15,1	13,55/-20,10	6,04/-3,84	2,02/4,96	3,24/3,94
HSS3c	15,87/-20,85	15,87/-20,85	14,62/-20,14	21,8/-18,5	14,06/-18,18	5,53/-3,15	2,25/6,33	3,93/5,87
HSS4c	14,83/-21,50	14,62/-21,50	14,62/-20,98	18,5/-17,4	12,32/-18,78	5,22/-1,92	2,14/9,12	3,53/9,04
HSS5c	15,31/-26,20	9,49/-26,20	9,55/-20,96	3,8/-17,5	6,67/-22,22	1,17/-2,68	5,03/7,46	3,21/6,53
Mean Values	15,21/-22,85	14,00/-22,80	13,28/-21,39	16,3/-17,0	11,87/-19,52	4,17/-3,74	3,07/6,09	4,04/5,54
Standard Deviations	0,52/2,60	2,58/2,55	2,13/-1,98	7,17/1,25	2,99/1,68	2,07/2,01	1,34/2,49	1,29/2,56

Cyclic load-displacement curve

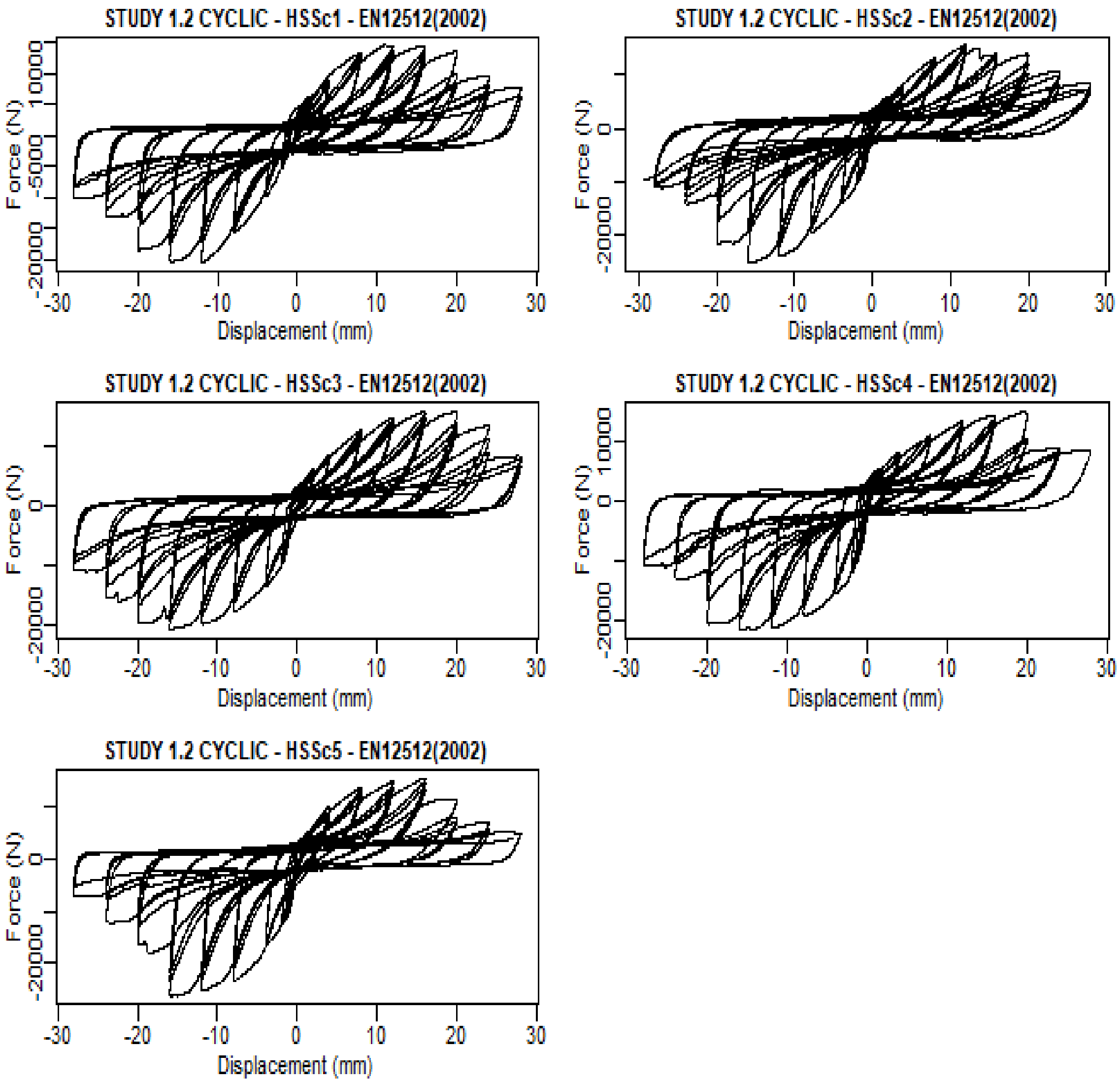

Figure C7: Cyclic load-displacement curves for each specimen in test group HSSc.

HSTc

NS-EN 12512 (2002)

Table C16: Values for HSTc from NS-EN 12512 (2002). Yield point method is the 1/6 procedure

Tension/ compression	Maximum Force (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HST1c	18,73/-31,74	14,98/-25,39	18,4/-18,2	14,63	7,6	1,94	2,44
HST2c	18,43/-25,22	14,75/-20,17	17,6/-18,1	11,83	2,4	4,85	7,21
HST3c	15,99/-27,95	12,80/-22,36	21,0/-20,0	13,62	7,7	1,77	2,73
HST4c	16,39/-27,19	13,11/-21,75	18,1/-20,1	12,54	7,3	1,73	2,49
HST5c	15,86/-23,85	12,68/-19,08	17,5/-17,9	11,99	5,2	2,29	3,34
Mean Values	17,08/-27,19	13,66/-21,75	18,5/-18,9	12,92	6,0	2,52	3,64
Standard Deviations	1,39/3,01	1,11/2,41	1,4/1,1	1,18	2,2	1,33	2,03

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Table C17: Values for HSTc calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

Tension/ compression	Peak Load (kN)	Maximum Load (kN)	Ultimate Load (kN)	Ultimate Slip (mm)	Yield Load (kN)	Yield Slip (mm)	Slip Modulus (kN/mm)	Ductility
HST1c	18,80/-31,95	18,49/-31,08	18,49/-31,09	15,3/-14,2	16,01/-25,08	7,91/-5,01	1,82/4,60	1,93/2,83
HST2c	18,54/-26,73	18,42/-24,44	18,42/-24,48	13,8/-11,8	15,72/-19,94	3,27/-6,86	4,42/3,16	4,21/1,72
HST3c	16,08/-28,17	16,08/-28,17	15,58/-25,87	17,4/-15,2	14,57/-23,80	8,03/-5,84	1,64/3,67	2,17/2,60
HST4c	16,45/-27,37	16,33/-25,50	16,34/-25,52	15,7/-13,8	14,11/-20,92	8,16/-6,66	1,54/3,39	1,92/2,08
HST5c	16,51/-24,40	16,27/-24,02	16,27/-24,02	14,0/-13,9	14,51/-20,02	6,33/-6,61	2,04/3,10	2,21/2,10
Mean Values	17,27/-27,72	17,12/-26,64	17,02/-26,20	15,2/-13,8	14,98/-21,95	6,74/-6,20	2,29/3,59	2,49/2,27
Standard Deviations	1,29/2,75	1,22/-2,96	1,34/2,84	1,46/1,23	0,83/2,35	2,08/0,77	1,20/0,61	0,97/0,44

Cyclic load-displacement curve

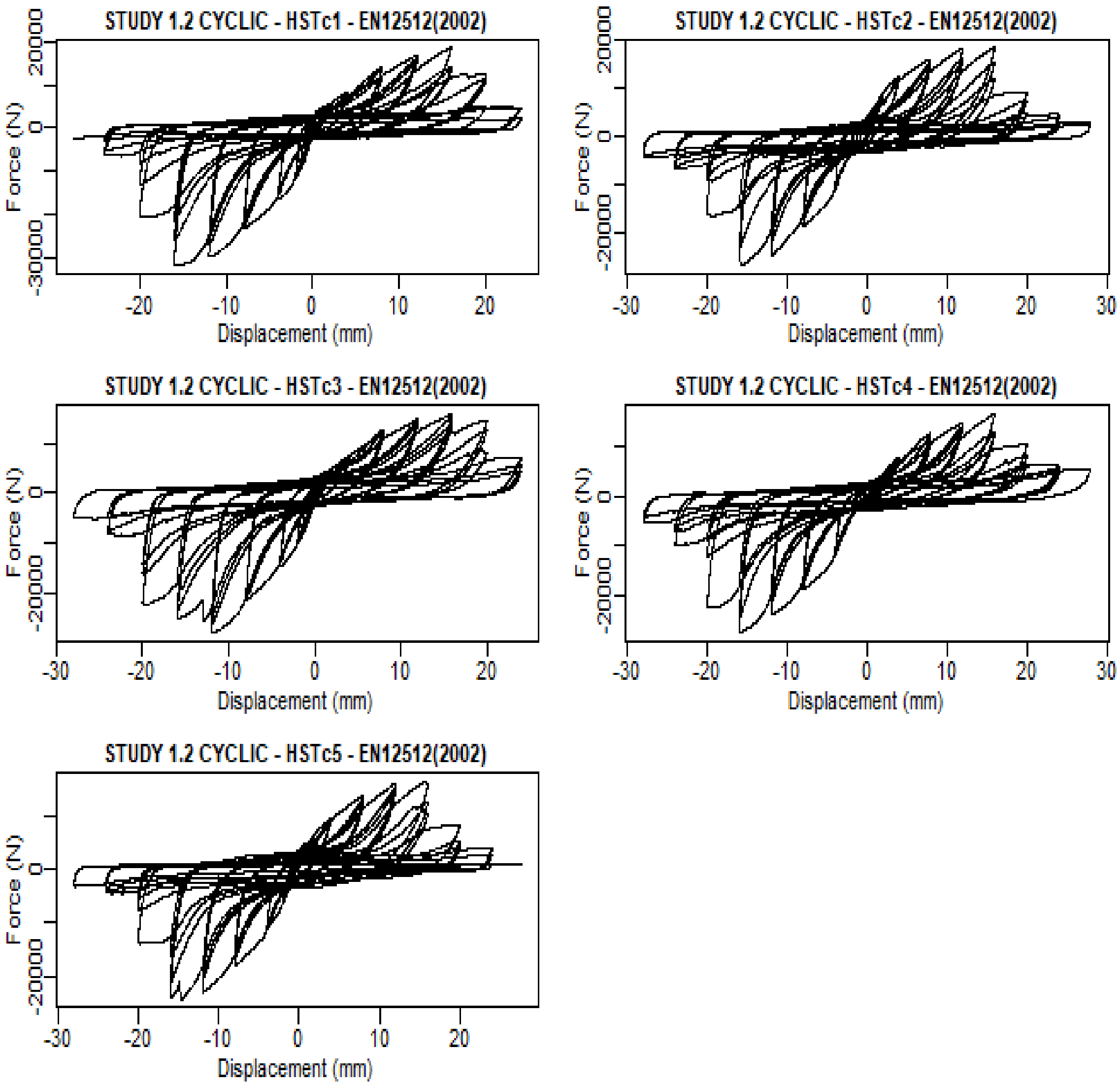

Figure C8: Cyclic load-displacement curves for each specimen in test group HSTc.

Equivalent viscous damping ratio – NS-EN 12512 (2002)

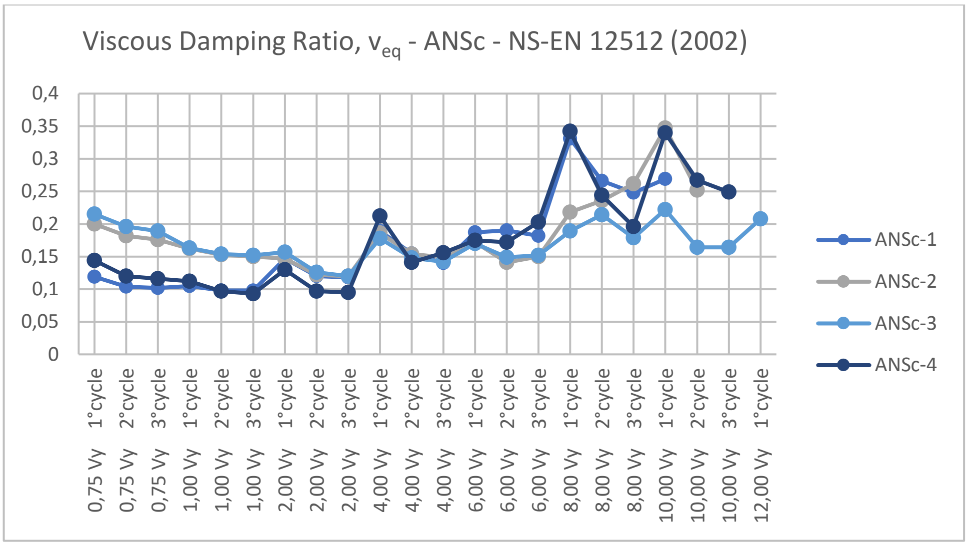

Figure C9: Viscous damping ratio for test group ANSc.

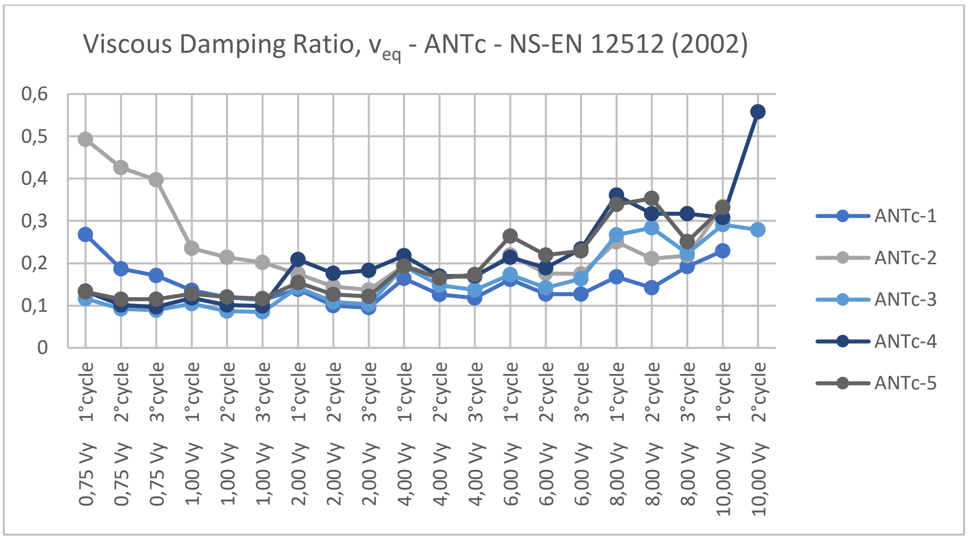

Figure C10: Viscous damping ratio for test group ANTc.

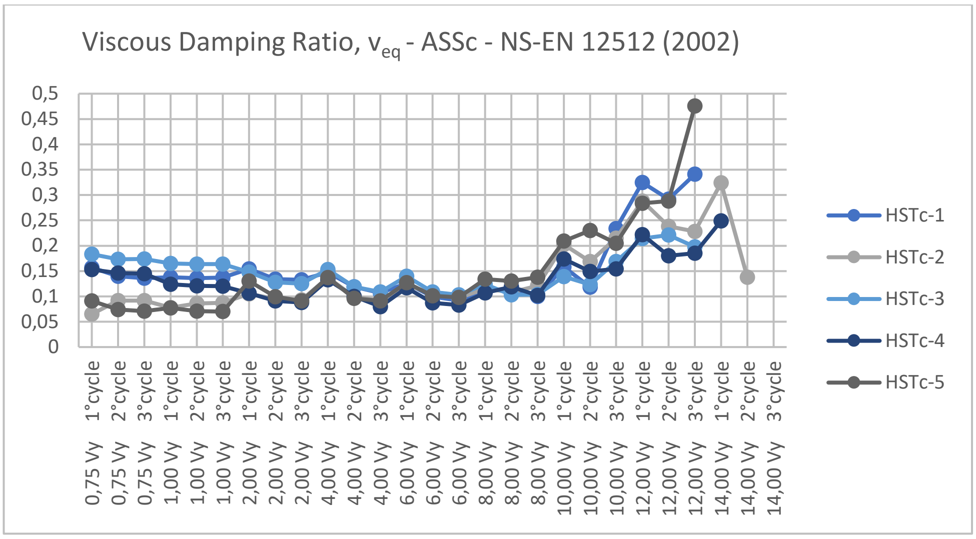

Figure C11: Viscous damping ratio for test group ASSc.

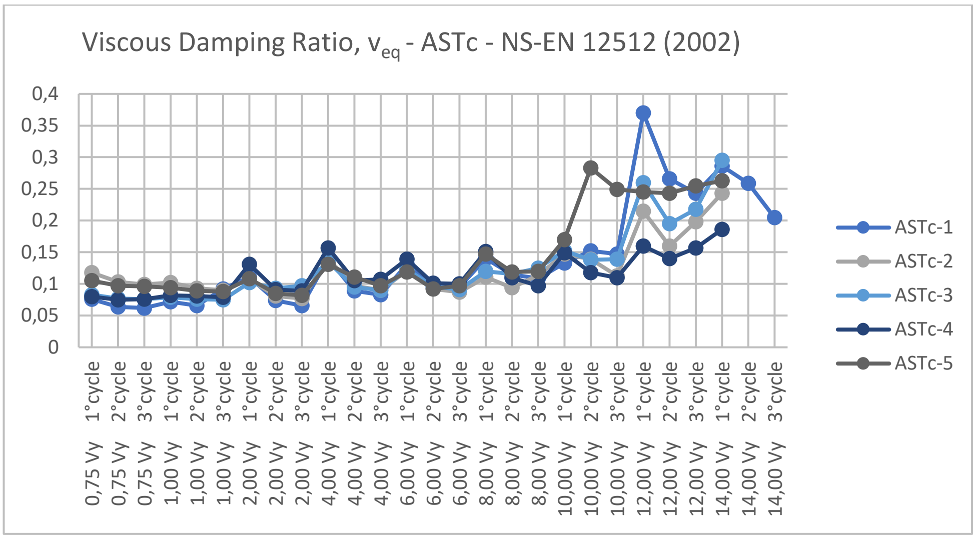

Figure C12: Viscous damping ratio for test group ASTc.

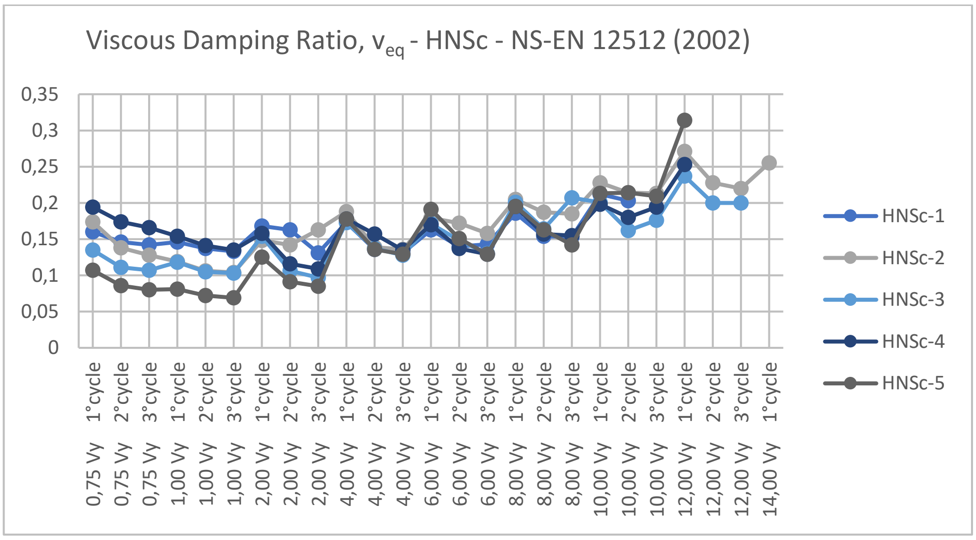

Figure C13: Viscous damping ratio for test group HNSc.

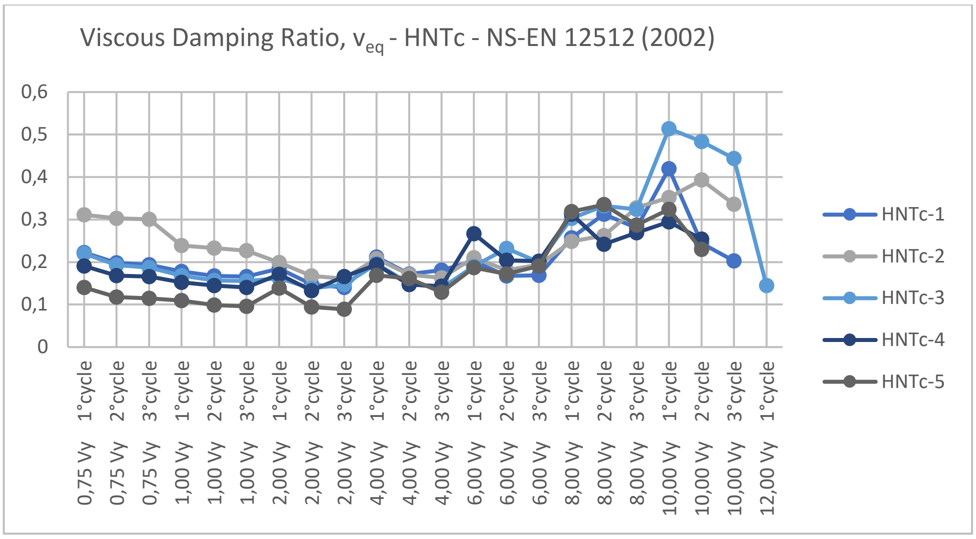

Figure C14: Viscous damping ratio for test group HNTc.

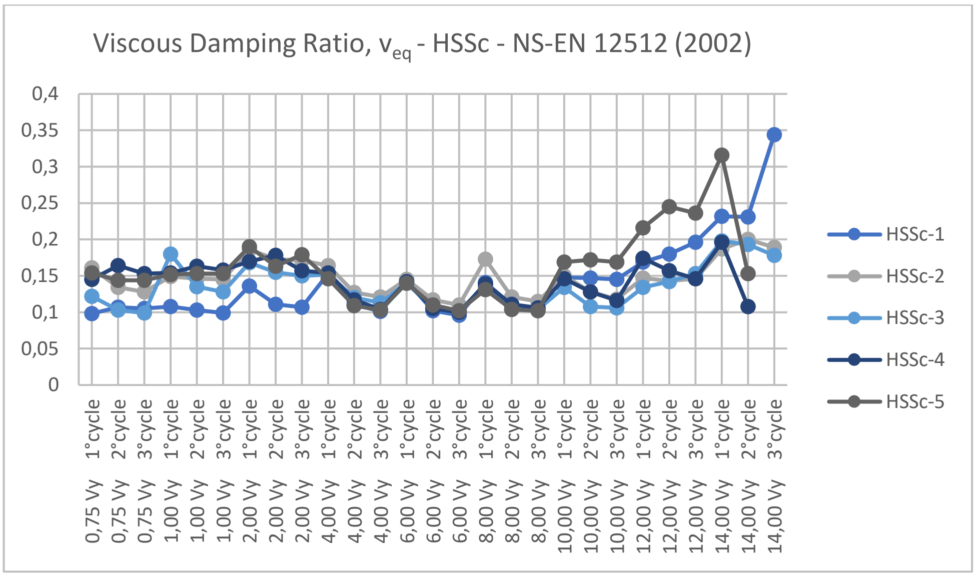

Figure C15: Viscous damping ratio for test group HSSc.

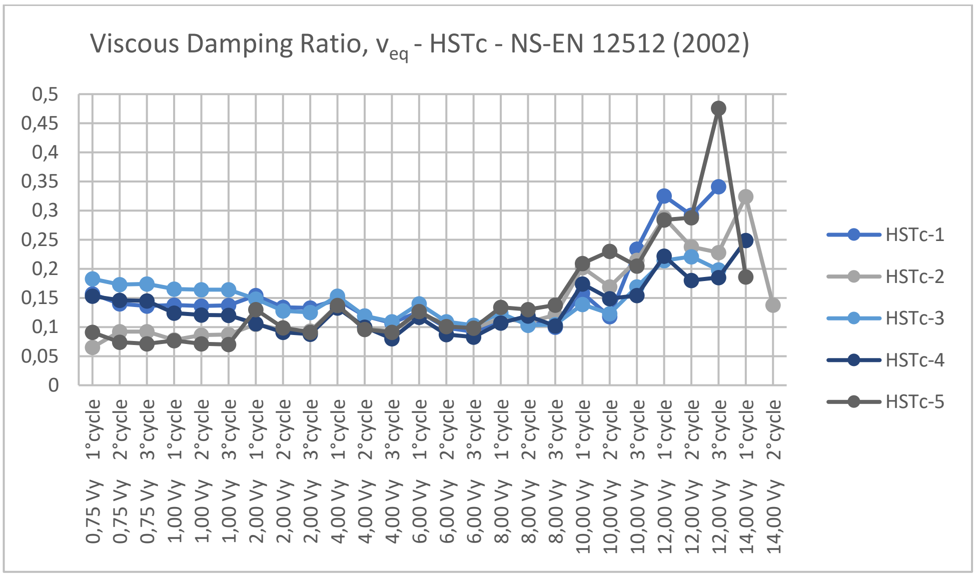

Figure C16: Viscous damping ratio for test group HSTc.

Equivalent viscous damping ratio – EN 12512 (2018) Draft

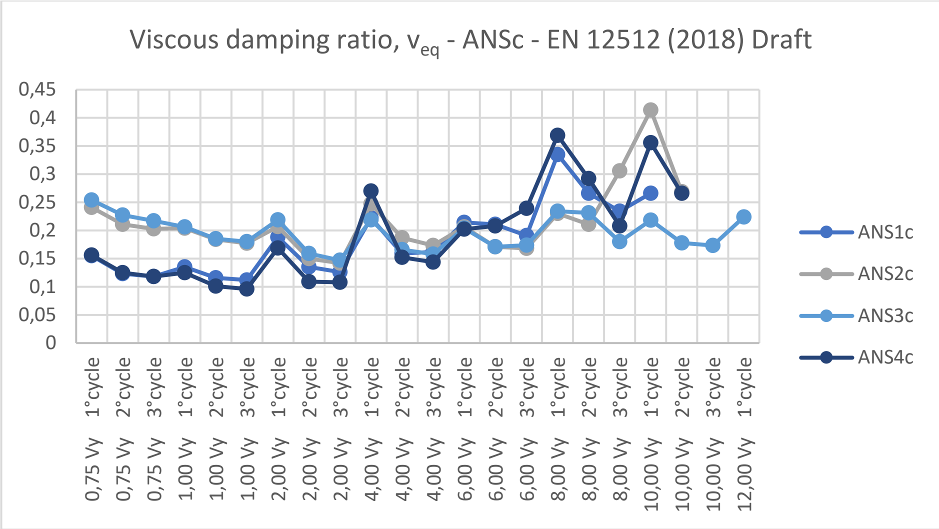

Figure C17: Viscous damping ratio for ANSc. Calculations from EN 12512 (2018) Draft version n°20180410.

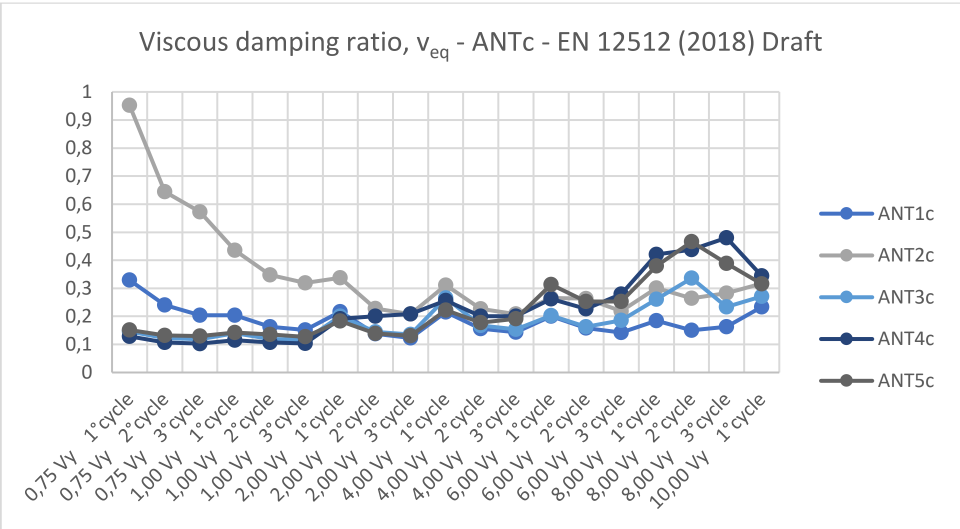

Figure C18: Viscous damping ratio for ANTc. Calculations from EN 12512 (2018) Draft version n°20180410.

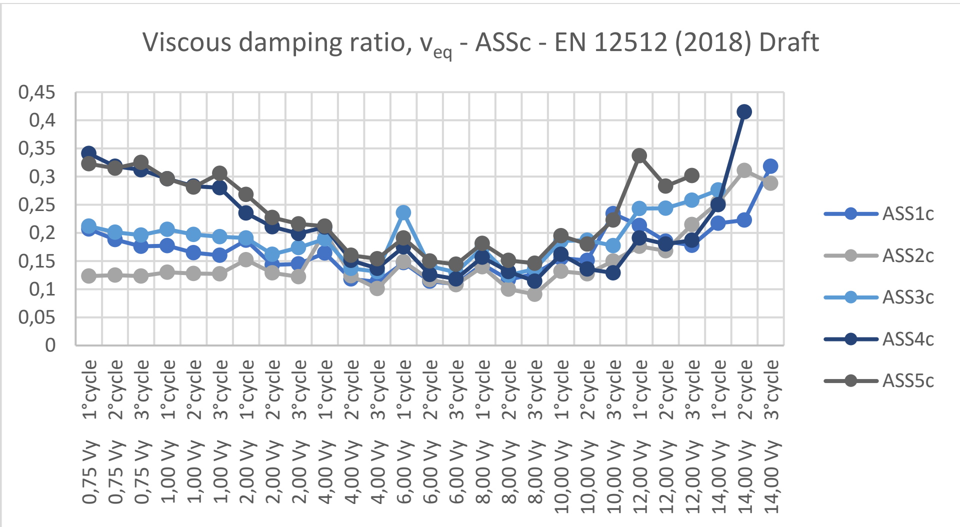

Figure C19: Viscous damping ratio for ASSc. Calculations from EN 12512 (2018) Draft version n°20180410.

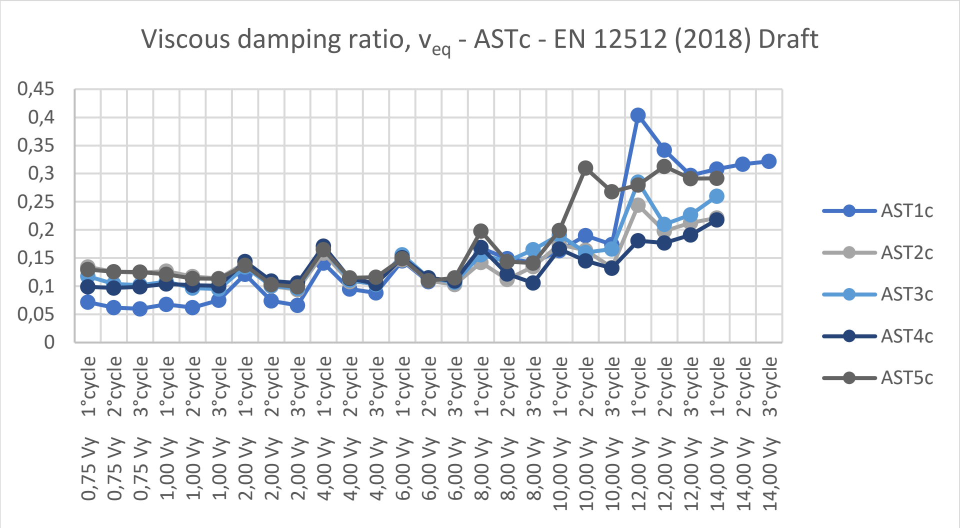

Figure C20: Viscous damping ratio for ASTc. Calculations from EN 12512 (2018) Draft version n°20180410.

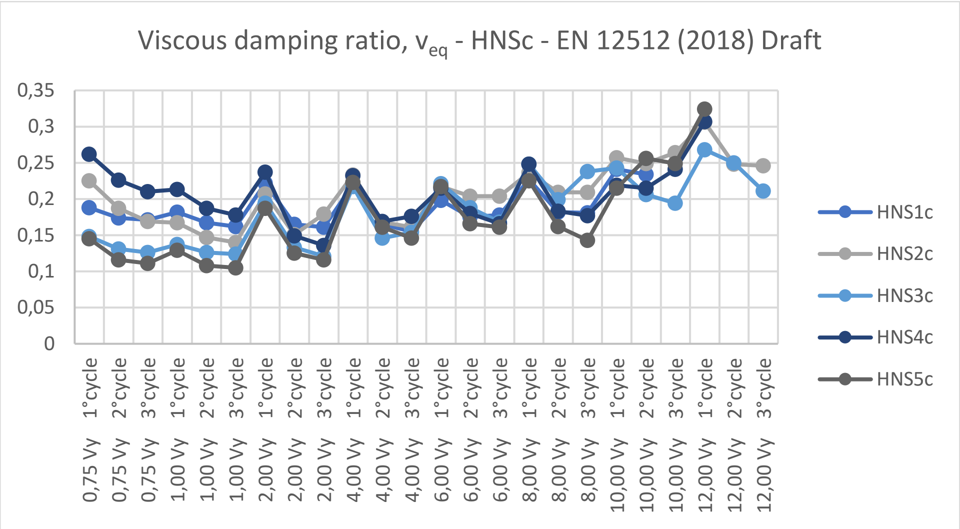

Figure C21: Viscous damping ratio for HNSc. Calculations from EN 12512 (2018) Draft version n°20180410.

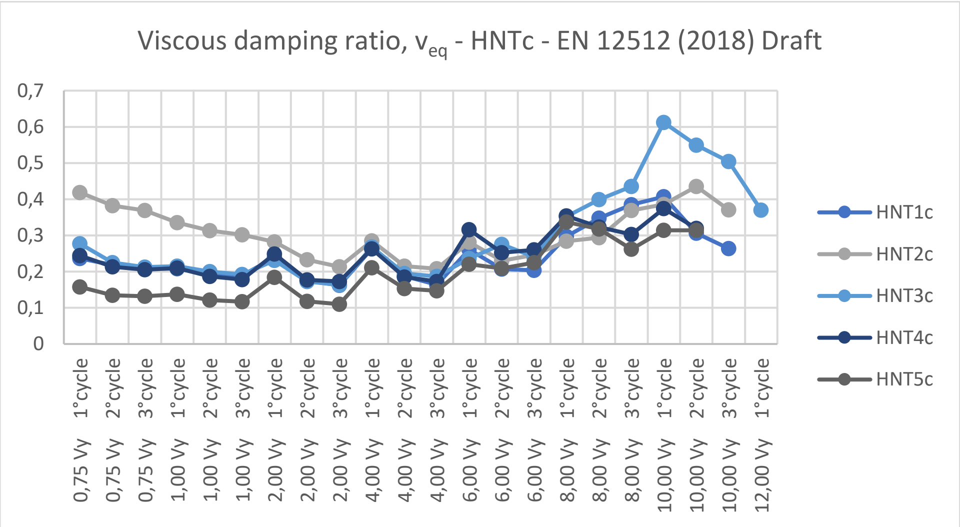

Figure C22: Viscous damping ratio for HNTc. Calculations from EN 12512 (2018) Draft version n°20180410.

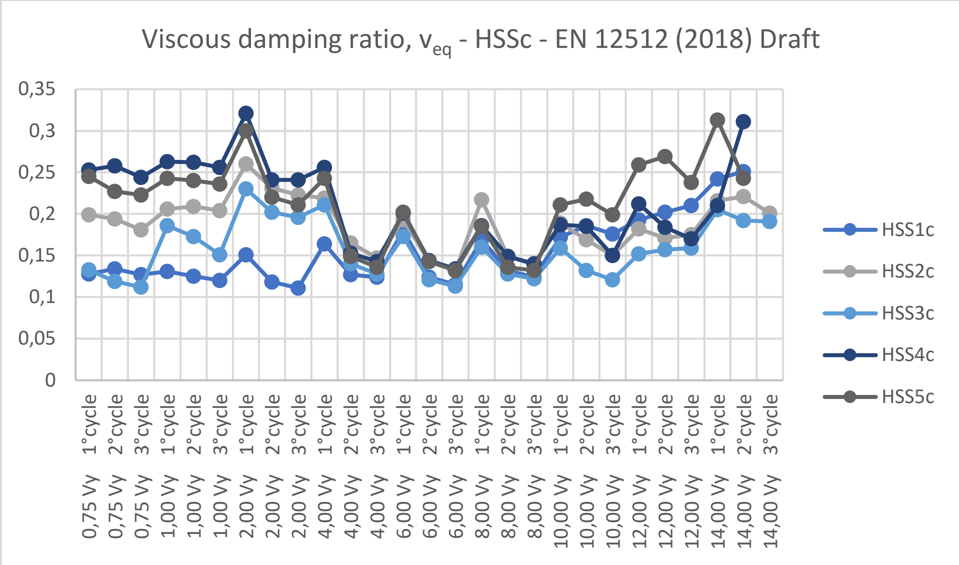

Figure C23: Viscous damping ratio for HSSc. Calculations from EN 12512 (2018) Draft version n°20180410.

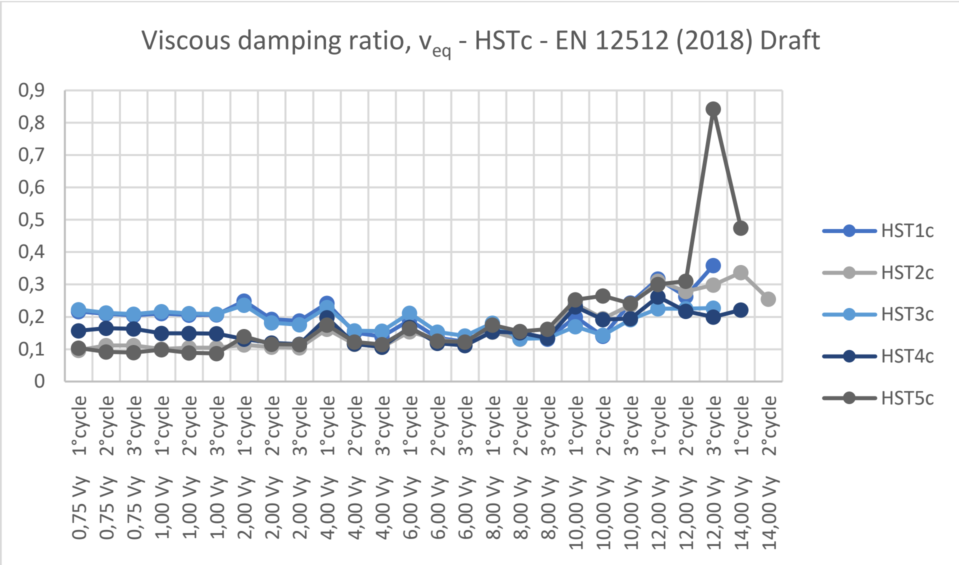

Figure C24: Viscous damping ratio for HSTc. Calculations from EN 12512 (2018) Draft version n°20180410.

Appendix D – Study 2

Moisture Content

Moisture content measured with moisturemeter for every specimen in each test group for study 2.

Table D1: Moisture content for specimens in Study 2.

specimen	moisture content % sill|TW	specimen	moisture content % sill|TW
HST-1s	15,4|12,5	AST-1s	15,2|12,6
HST-2s	15,0|11,8	AST-2s	15,7|12,5
HST-3s	15,8|12,1	AST-3s	15,0|12,6
HST-4s	15,2|12,9	AST-4s	14,8|12,6
HST-5s	15,2|12,6	AST-5s	15,2|12,7
HST-6s	15,2|11,7	AST-6s	15,5|13,0
HST-7s	14,7|11,6	AST-7s	15,8|13,4
HST-8s	14,8|11,6	AST-8s	14,6|12,7
HSS-1s	14,3|12,3	ASS-1s	14,4|12,0
HSS-2s	13,2|12,4	ASS-2s	13,9|11,6
HSS-3s	12,3|12,2	ASS-3s	12,2|12,0
HSS-4s	13,5|12,1	ASS-4s	14,7|12,7
HSS-5s	14,5|12,4	ASS-5s	12,6|13,1
HSS-6s	14,4|11,4	ASS-6s	12,3|12,2
HSS-7s	13,3|12,2	ASS-7s	12,9|13,0
HSS-8s	12,9|12,0	ASS-8s	14,3|11,8
HNT-1s	14,9|12,1	ANT-1s	15,1|12,9
HNT-2s	15,6|12,7	ANT-2s	15,7|13,0
HNT-3s	15,6|12,7	ANT-3s	14,9|12,6
HNT-4s	15,0|12,2	ANT-4s	16,5|12,4
HNT-5s	15,9|12,4	ANT-5s	16,1|12,5
HNT-6s	15,8|12,7	ANT-6s	15,8|12,3
HNT-7s	15,7|12,8	ANT-7s	15,2|12,2
HNT-8s	13,5|11,2	ANT-8s	12,9|12,0
HNS-1s	14,0|13,1	ANS-1s	13,4|12,5
HNS-2s	13,6|12,9	ANS-2s	13,9|13,1
HNS-3s	11,4|12,9	ANS-3s	13,1|12,2
HNS-4s	13,9|12,1	ANS-4s	13,2|12,8
HNS-5s	13,4|12,8	ANS-5s	13,4|12,8
HNS-6s	12,1|12,0	ANS-6s	13,7|11,7
HNS-7s	13,0|12,3	ANS-7s	14,0|12,0
HNS-8s	12,5|11,5	ANS-8s	11,4|12,6

ANSs

NS-ISO 6891 (1991)

Table D2: Values for ANSs from NS-ISO 6891 (1991). Yield point method is the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
ANS1	6,40	6,92	0,31	14,73
ANS2	5,92	5,55	0,37	4,49
ANS3	5,46	4,10	0,38	4,00
ANS4	5,72	5,79	0,31	4,73
ANS5	5,33	3,66	0,50	3,11
ANS6	5,16	10,43	0,31	4,57
ANS7	5,55	4,61	0,37	3,80
ANS8	6,26	1,91	0,08	18,50
Mean Values	5,72	5,37	0,33	7,24
Standard Deviations	0,44	2,54	0,12	5,90

NS-EN 12512 (2002)

Table D3: Values for ANSs from NS-EN 1251(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANS1s	6,40	6,10	9,9	4,67	1,09	4,28	9,11
ANS2s	5,92	4,74	12,6	4,67	1,08	4,33	11,70
ANS3s	5,46	4,89	9,8	4,58	1,16	3,96	8,50
ANS4s	5,72	4,57	18,0	5,27	1,13	4,67	15,93
ANS5s	5,33	5,22	4,2	4,79	1,70	2,82	2,47
ANS6s	5,16	4,13	15,6	3,90	0,92	4,22	16,90
ANS7s	5,55	5,42	4,6	4,03	1,36	2,96	3,40
ANS8s	6,25	5,00	6,8	4,95	0,47	10,47	14,40
Mean Values	5,72	5,01	10,20	4,61	1,11	4,71	10,30
Standard Deviations	0,44	0,59	4,99	0,45	0,35	2,42	5,45

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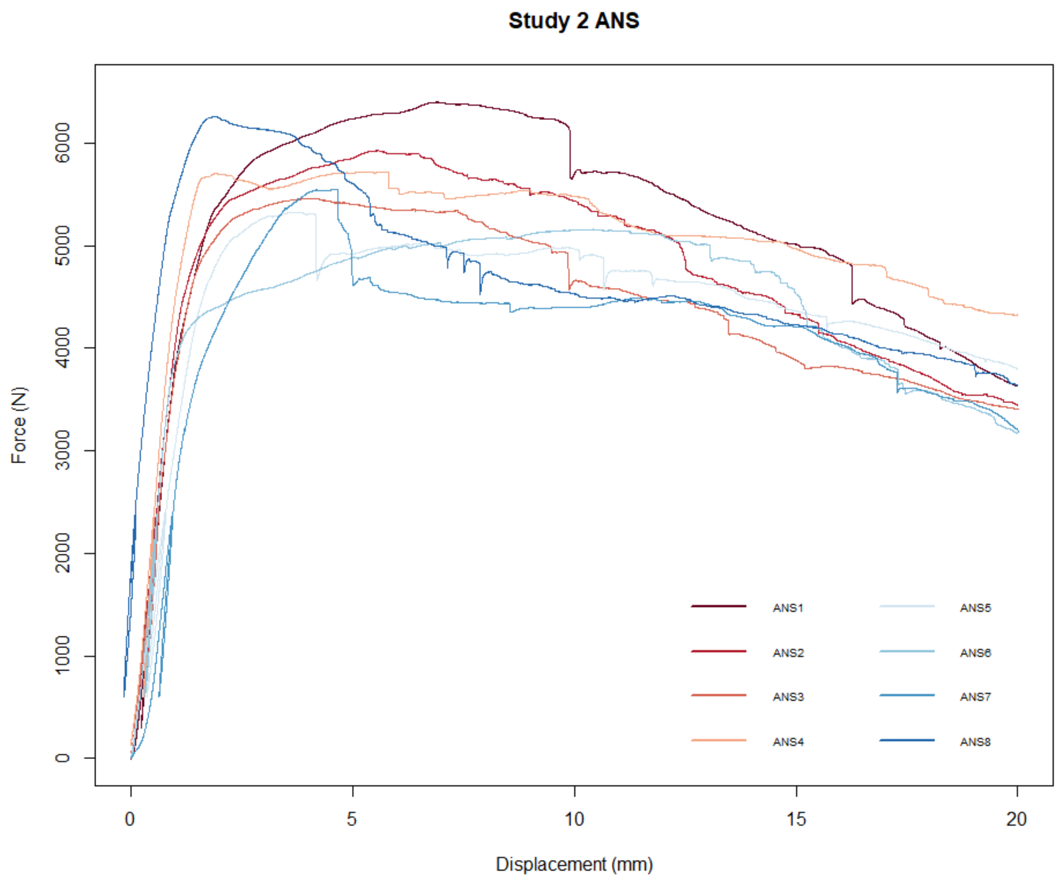
Table D4: Values for ANSs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANS1s	6,40	6,40	6,10	9,9	6,06	1,36	5,09	7,28
ANS2s	5,92	5,92	4,74	12,6	5,51	1,27	4,48	9,97
ANS3s	5,46	5,46	4,89	9,8	5,22	1,32	4,00	7,46
ANS4s	5,72	5,72	4,57	18,0	5,30	1,13	4,73	15,85
ANS5s	5,33	5,33	5,18	4,2	5,21	1,85	2,78	2,26
ANS6s	5,16	5,16	4,13	15,6	4,85	1,13	4,57	13,80
ANS7s	5,55	5,55	5,33	4,7	4,91	1,59	3,80	2,93
ANS8s	6,25	6,25	5,00	6,8	5,67	0,58	6,86	11,81
Mean Values	5,72	5,72	4,99	10,20	5,34	1,28	4,54	8,92
Standard Deviations	0,44	0,44	0,58	4,99	0,40	0,37	1,17	4,88



ANTs

NS-ISO 6891 (1991)

Table D5: Values for ANTs calculated from NS-ISO 6891 (1991). Yield point method from the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
ANT1	5,48	4,50	0,41	5,85
ANT2	3,86	3,23	0,27	3,39
ANT3	5,09	5,52	0,24	5,66
ANT4	4,10	9,21	0,21	4,62
ANT5	4,99	3,39	0,32	5,69
ANT6	4,26	3,54	0,20	4,79
ANT7	4,43	5,28	0,32	4,33
ANT8	4,29	2,93	0,28	4,14
Mean Values	4,56	4,70	0,28	4,81
Standard Deviations	0,56	2,06	0,07	0,87

NS-EN 12512 (2002)

Table D6: Values for ANTs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANT1s	5,48	4,39	10,3	4,12	1,35	3,05	7,66
ANT2s	3,86	3,09	14,3	3,09	0,97	3,19	14,71
ANT3s	5,09	4,08	19,9	3,54	0,61	5,80	32,68
ANT4s	4,09	3,28	19,8	2,61	0,68	3,84	29,15
ANT5s	4,99	4,00	16,8	3,68	0,80	4,58	20,93
ANT6s	4,25	3,40	14,2	3,61	0,94	3,82	15,01
ANT7s	4,43	3,54	19,1	3,72	1,12	3,32	17,04
ANT8s	4,28	4,02	3,1	3,45	1,03	3,35	3,00
Mean Values	4,56	3,72	14,7	3,48	0,94	3,87	17,52
Standard Deviations	0,56	0,46	5,75	0,45	0,24	0,92	9,99

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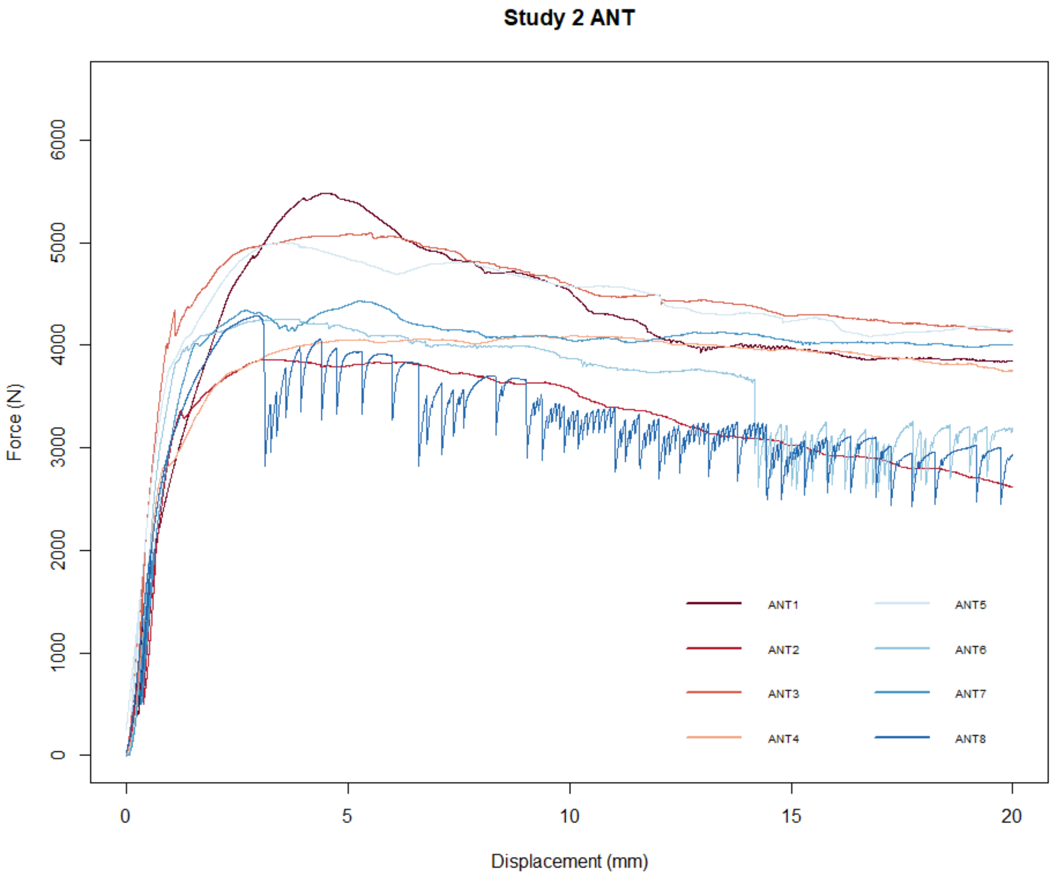
Table D7: Values for ANTs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ANT1s	5,48	5,48	4,39	10,3	4,83	1,58	3,11	6,55
ANT2s	3,86	3,86	3,09	14,3	3,57	1,11	3,39	12,84
ANT3s	5,09	5,09	4,08	19,9	4,57	0,74	8,12	27,05
ANT4s	4,09	4,09	3,28	19,8	3,92	0,96	4,61	20,59
ANT5s	4,99	4,99	4,00	16,8	4,55	1,01	4,28	16,68
ANT6s	4,25	4,25	3,40	14,2	3,98	1,03	4,35	13,78
ANT7s	4,43	4,43	3,54	19,1	4,12	1,23	3,73	15,57
ANT8s	4,28	4,28	3,97	3,1	3,92	1,17	3,45	2,65
Mean Values	4,56	4,56	3,72	14,7	4,18	1,10	4,38	14,46
Standard Deviations	0,56	0,56	0,45	5,75	0,43	0,24	1,60	7,63



ASSs

NS-ISO 6891 (1991)

Table D8: Values for ASSs calculated from NS-ISO 6891 (1991). Yield point method from the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
ASS1	11,14	6,28	0,63	12,56
ASS2	14,63	12,81	1,11	6,71
ASS3	12,39	5,66	0,56	7,42
ASS4	11,75	6,32	0,65	5,56
ASS5	11,48	6,76	0,70	4,97
ASS6	13,70	4,80	0,62	9,33
ASS7	11,42	4,94	0,65	5,09
ASS8	12,66	6,42	0,82	5,34
Mean Values	12,40	6,75	0,72	7,12
Standard Deviations	1,23	2,55	0,18	2,65

NS-EN 12512 (2002)

Table D9: Values for ASSs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ASS1s	11,14	8,91	11,8	8,52	1,93	4,41	6,12
ASS2s	14,63	11,71	16,3	9,75	2,48	3,94	6,56
ASS3s	12,39	9,91	10,0	8,33	1,34	6,23	7,47
ASS4s	11,75	9,40	12,9	7,72	1,49	5,17	8,66
ASS5s	11,48	9,19	11,6	7,89	1,57	5,02	7,39
ASS6s	13,70	13,28	5,4	10,84	1,84	5,90	2,95
ASS7s	11,42	9,14	9,8	8,47	1,65	5,12	5,90
ASS8s	12,66	10,12	12,2	10,49	2,46	4,27	4,95
Mean Values	12,40	10,21	11,2	9,00	1,84	5,01	6,25
Standard Deviations	1,23	1,53	3,10	1,19	0,43	0,79	1,75

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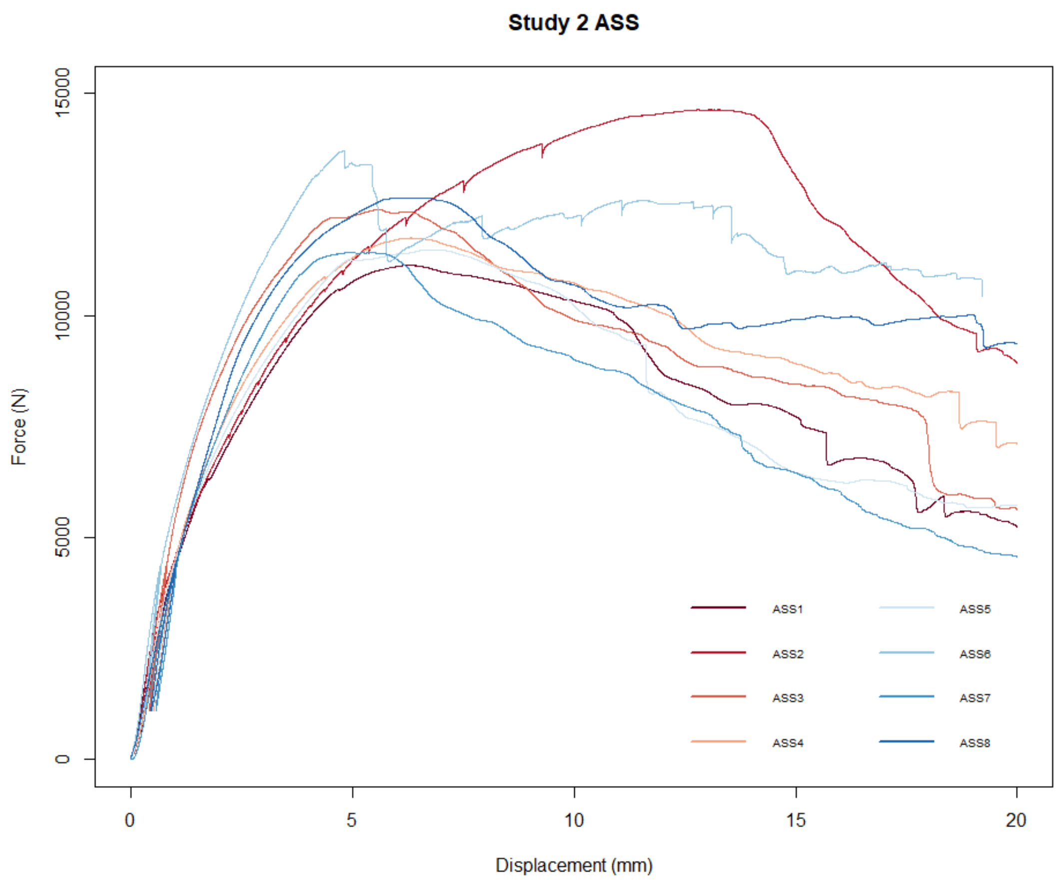
Table D10: Values for ASSs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
ASS1s	11,14	11,14	8,91	11,8	10,08	2,27	4,55	5,20
ASS2s	14,63	14,63	11,71	16,3	12,87	3,26	3,99	4,99
ASS3s	12,39	12,39	9,91	10,0	11,09	1,69	7,90	5,92
ASS4s	11,75	11,75	9,40	12,9	10,50	1,91	6,72	6,78
ASS5s	11,48	11,48	9,07	11,6	10,29	1,96	6,21	5,93
ASS6s	13,70	13,70	13,12	5,4	11,68	1,98	5,92	2,75
ASS7s	11,42	11,42	9,14	9,8	10,10	1,89	6,74	5,15
ASS8s	12,66	12,66	10,12	12,2	11,28	2,64	4,26	4,60
Mean Values	12,40	12,40	10,17	11,2	10,99	2,20	5,79	5,17
Standard Deviations	1,23	1,23	1,49	3,09	0,96	0,52	1,39	1,19



ASTs

NS-ISO 6891 (1991)

Table D11: Values for ASTs calculated from NS-ISO 6891 (1991). Yield point method from the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
AST1	13,59	7,60	0,52	15,75
AST2	13,48	5,65	0,76	6,37
AST3	11,60	4,88	0,52	6,71
AST4	13,59	11,23	0,80	5,16
AST5	12,20	4,99	0,82	4,83
AST6	12,09	5,60	0,54	6,18
AST7	14,78	5,50	0,83	6,77
AST8	13,88	10,62	0,93	4,61
Mean Values	13,15	7,01	0,71	7,05
Standard Deviations	1,08	2,56	0,16	3,62

NS-EN 12512 (2002)

Table D12: Values for ASTs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
AST1s	13,59	10,87	12,9	9,59	1,49	6,43	8,66
AST2s	13,48	10,79	8,8	9,59	1,62	5,90	5,43
AST3s	11,60	9,28	16,3	9,13	1,58	5,77	10,30
AST4s	13,59	10,87	15,6	9,50	1,92	4,96	8,12
AST5s	12,20	9,76	8,2	10,65	2,38	4,48	3,44
AST6s	12,09	9,67	14,0	9,28	1,72	5,39	8,15
AST7s	14,78	11,83	7,6	11,97	2,18	5,49	3,49
AST8s	13,88	11,11	15,7	10,39	2,30	4,53	6,83
Mean Values	13,15	10,52	12,4	10,01	1,90	5,37	6,80
Standard Deviations	1,08	0,86	3,64	0,95	0,35	0,68	2,49

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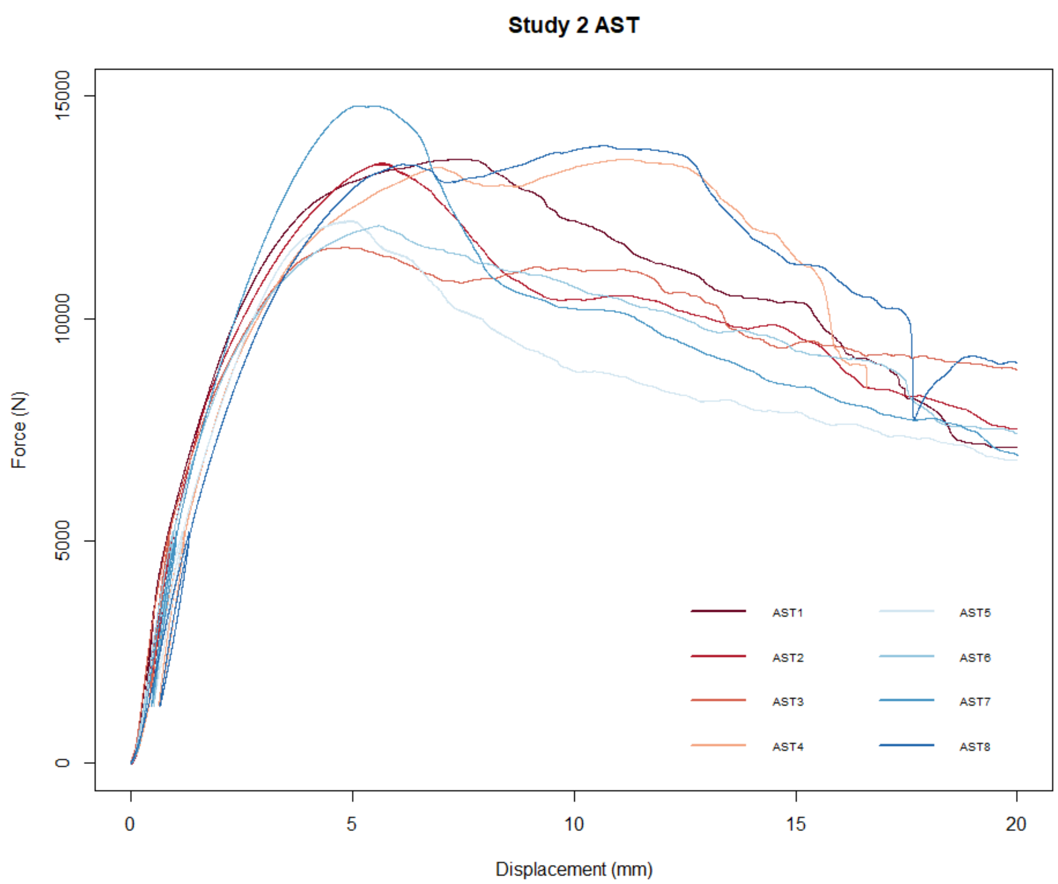
Table D13: Values for ASTs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
AST1s	13,59	13,59	10,87	12,9	12,16	1,85	7,09	6,97
AST2s	13,48	13,48	10,79	8,8	11,85	1,96	6,82	4,51
AST3s	11,60	11,60	9,28	16,3	10,52	1,82	5,86	8,95
AST4s	13,59	13,59	10,87	15,6	12,50	2,39	6,38	6,52
AST5s	12,20	12,20	9,76	8,2	10,94	2,44	4,57	3,34
AST6s	12,09	12,09	9,67	14,0	10,71	1,98	5,59	7,09
AST7s	14,78	14,78	11,83	7,6	13,17	2,37	6,20	3,20
AST8s	13,88	13,88	11,11	15,7	12,69	2,71	5,59	5,79
Mean Values	13,15	13,15	10,52	12,4	11,82	2,19	6,01	5,80
Standard Deviations	1,08	1,08	0,86	3,64	0,99	0,33	0,80	2,00



HNSs

NS-ISO 6891 (1991)

Table D14: Values for HNSs calculated from NS-ISO 6891 (1991). Yield point method from the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
HNS1	5,34	11,45	0,35	10,02
HNS2	5,35	9,43	0,49	2,62
HNS3	5,07	6,90	0,32	2,73
HNS4	6,25	8,93	0,41	5,17
HNS5	5,68	10,34	0,37	4,72
HNS6	5,12	7,61	0,36	3,28
HNS7	6,07	10,50	0,39	5,39
HNS8	5,10	8,84	0,40	2,29
Mean Values	5,50	9,25	0,39	4,53
Standard Deviations	0,46	1,52	0,05	2,53

NS-EN 12512 (2002)

Table D15: Values for HNSs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNS1s	5,34	4,94	13,1	2,94	0,89	3,30	14,72
HNS2s	5,35	4,28	20,0	2,76	1,02	2,70	19,58
HNS3s	5,07	4,76	7,5	2,09	1,14	1,84	6,57
HNS4s	6,25	5,84	9,2	3,15	0,97	3,25	9,48
HNS5s	5,68	5,63	10,4	2,29	0,63	3,62	16,31
HNS6s	5,12	4,86	8,1	2,07	0,69	3,00	11,83
HNS7s	6,07	4,86	20,0	2,89	0,82	3,53	24,39
HNS8s	5,10	4,96	8,9	2,14	0,96	2,24	9,27
Mean Values	5,50	5,02	12,1	2,54	0,89	2,94	14,02
Standard Deviations	0,46	0,50	5,14	0,44	0,17	0,63	5,95

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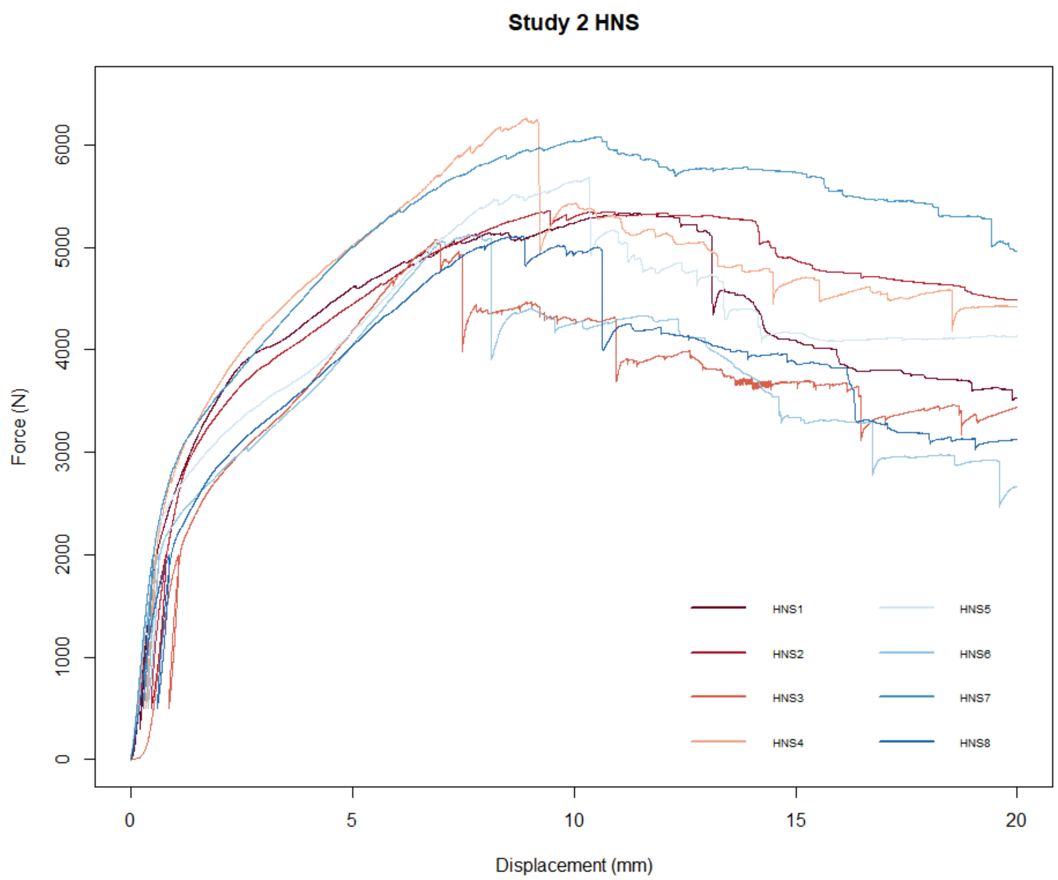
Table D16: Values for HNSs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNS1s	5,34	5,34	4,94	13,2	4,71	1,41	3,43	9,35
HNS2s	5,35	5,35	4,28	20,0	4,76	1,52	3,97	13,11
HNS3s	5,07	5,07	4,78	7,5	3,99	1,47	5,68	5,08
HNS4s	6,25	6,25	5,98	9,2	5,00	1,53	3,27	6,01
HNS5s	5,68	5,68	5,44	10,4	4,42	1,05	5,13	9,88
HNS6s	5,12	5,12	4,88	8,2	3,89	1,05	5,05	7,78
HNS7s	6,07	6,07	4,86	20,0	5,31	1,52	3,47	13,17
HNS8s	5,10	5,10	4,96	8,9	4,07	1,38	4,57	6,43
Mean Values	5,50	5,50	5,02	12,2	4,52	1,37	4,32	8,85
Standard Deviations	0,46	0,46	0,50	5,13	0,51	0,20	0,91	3,10



HNTs

NS-ISO 6891 (1991)

Table D17: Values for HNTs calculated from NS-ISO 6891 (1991). Yield point method from the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
HNT1	6,13	15,00	0,71	3,14
HNT2	5,57	10,01	0,47	3,16
HNT3	6,13	14,42	0,62	3,19
HNT4	5,17	10,96	0,64	1,96
HNT5	6,16	10,34	0,50	4,66
HNT6	5,38	15,00	0,51	2,45
HNT7	5,43	10,39	0,55	2,34
HNT8	5,39	14,34	0,67	2,30
Mean Values	5,67	12,56	0,58	2,90
Standard Deviations	0,40	2,31	0,09	0,85

NS-EN 12512 (2002)

Table D18: Values for HNTs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNT1s	6,19	4,95	20,0	2,92	1,42	2,06	14,08
HNT2s	5,57	5,18	13,7	2,77	1,24	2,23	10,98
HNT3s	6,13	4,90	20,0	2,78	1,25	2,22	15,97
HNT4s	5,17	4,14	20,0	3,05	1,91	1,60	10,47
HNT5s	6,16	5,22	17,2	2,87	1,01	2,84	16,99
HNT6s	5,43	4,35	19,9	2,60	1,06	2,45	18,79
HNT7s	5,43	5,19	14,1	2,60	1,20	2,16	11,76
HNT8s	5,39	4,31	20,0	2,75	1,22	2,26	16,44
Mean Values	5,68	4,78	18,1	2,79	1,29	2,23	14,44
Standard Deviations	0,41	0,45	2,78	0,16	0,28	0,35	3,09

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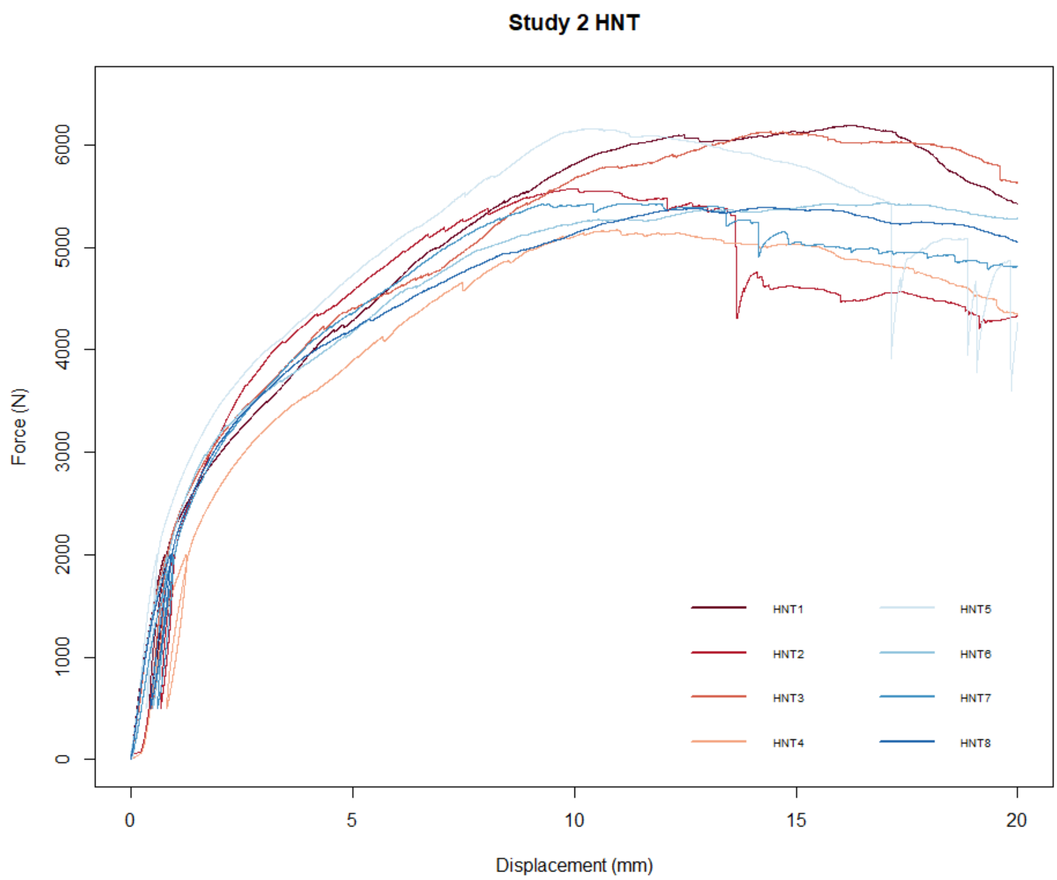
Table D19: Values for HNTs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HNT1s	6,19	6,19	4,95	20,0	5,37	2,43	2,42	8,21
HNT2s	5,57	5,57	5,12	13,6	4,93	1,80	3,86	7,54
HNT3s	6,13	6,13	4,90	20,0	5,32	2,15	2,81	9,28
HNT4s	5,17	5,17	4,14	20,0	4,59	2,79	1,73	7,15
HNT5s	6,16	6,16	5,15	17,2	5,34	1,70	3,56	10,09
HNT6s	5,43	5,43	4,35	19,9	4,89	1,69	3,65	11,81
HNT7s	5,43	5,43	5,17	14,1	4,80	1,84	3,43	7,66
HNT8s	5,39	5,39	4,31	20,0	4,84	1,95	2,86	10,26
Mean Values	5,68	5,68	4,76	18,1	5,01	2,05	3,04	9,00
Standard Deviations	0,41	0,41	0,43	2,79	0,30	0,39	0,72	1,64



HSSs

NS-ISO 6891 (1991)

Table D20: Values for HSSs calculated from NS-ISO 6891 (1991). Yield point method from the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
HSS1	7,84	5,69	0,43	12,60
HSS2	7,80	8,84	0,43	12,77
HSS3	7,42	5,27	0,39	10,97
HSS4	7,12	6,12	0,32	11,14
HSS5	7,20	4,23	0,31	13,20
HSS6	8,86	7,34	0,36	21,82
HSS7	7,13	4,89	0,40	8,63
HSS8	8,80	6,06	0,51	19,48
Mean Values	7,77	6,05	0,40	13,83
Standard Deviations	0,71	1,46	0,06	4,49

NS-EN 12512 (2002)

Table D21: Values for HSSs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HSS1s	8,24	7,72	11,3	5,36	1,94	2,77	5,84
HSS2s	7,80	7,50	9,0	5,13	4,32	1,19	2,08
HSS3s	7,77	6,86	5,3	4,37	1,11	3,93	4,73
HSS4s	7,51	6,78	6,1	4,21	1,75	2,40	3,49
HSS5s	7,32	7,07	7,6	4,30	0,84	5,11	8,97
HSS6s	8,96	8,47	7,4	4,59	0,88	5,25	8,43
HSS7s	7,13	6,85	4,9	4,82	1,70	2,84	2,89
HSS8s	9,24	8,67	12,6	6,44	1,89	3,41	6,67
Mean Values	8,00	7,49	8,0	4,90	1,80	3,36	5,39
Standard Deviations	0,76	0,74	2,79	0,74	1,11	1,37	2,54

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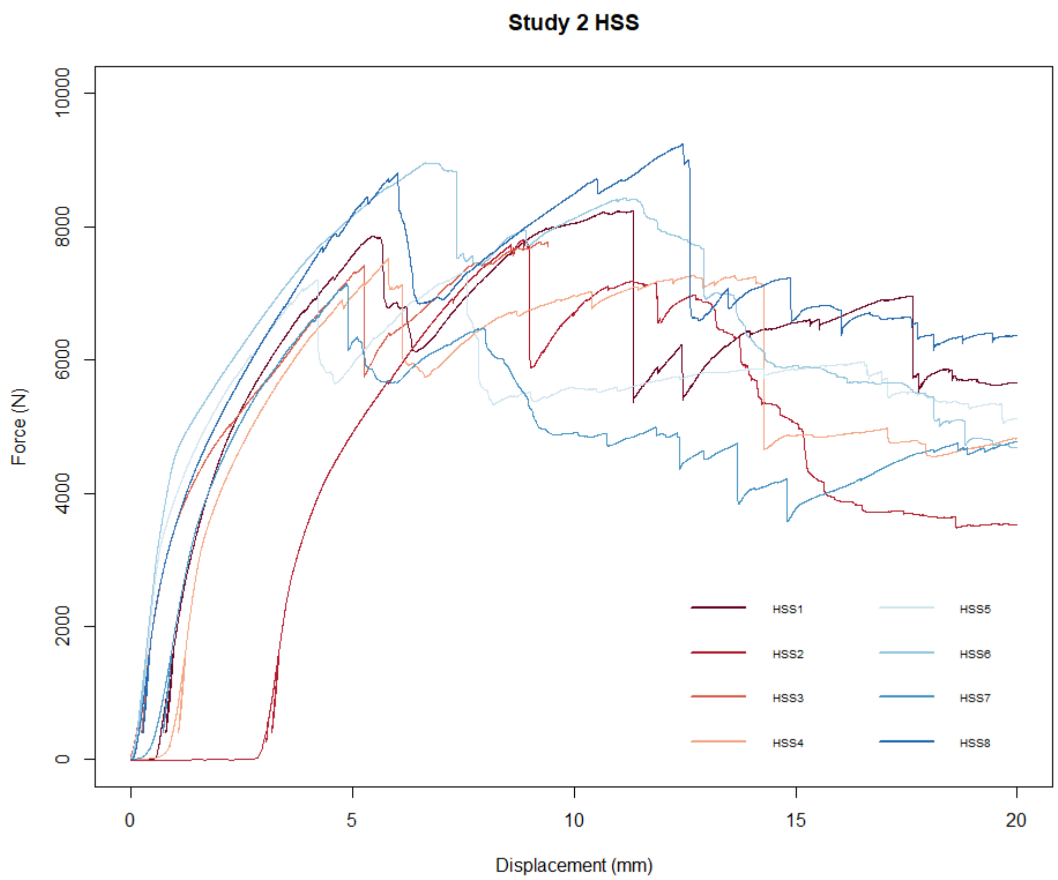
Table D22: Values for HSSs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HSS1s	8,24	8,24	7,88	11,3	7,11	2,35	4,24	4,81
HSS2s	7,80	7,80	7,28	9,0	7,26	4,90	3,71	1,84
HSS3s	7,77	7,42	7,16	5,3	5,83	1,39	4,70	3,80
HSS4s	7,51	7,51	6,90	6,1	6,27	2,12	5,57	2,87
HSS5s	7,32	7,32	7,18	7,6	6,18	1,17	5,66	6,44
HSS6s	8,96	8,96	8,47	7,4	7,42	1,35	5,97	5,45
HSS7s	7,13	7,13	6,91	4,9	5,92	1,94	4,45	2,52
HSS8s	9,24	9,24	7,40	12,6	7,73	2,26	3,45	5,58
Mean Values	8,00	7,95	7,40	8,0	6,71	2,19	4,72	4,16
Standard Deviations	0,76	0,79	0,53	2,80	0,74	1,18	0,93	1,65



HSTs

NS-ISO 6891 (1991)

Table D23: Values for HSTs calculated from NS-ISO 6891 (1991). Yield point method from the iso-standard.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
HST1	11,41	12,75	0,68	47,13
HST2	11,64	15,00	1,34	22,59
HST3	12,39	15,00	1,06	43,75
HST4	11,40	13,86	0,98	45,96
HST5	11,62	10,37	0,79	3,43
HST6	10,77	11,36	0,84	2,12
HST7	11,14	12,39	0,84	2,09
HST8	11,29	13,47	0,84	2,35
Mean Values	11,46	13,03	0,92	21,18
Standard Deviations	0,47	1,65	0,21	21,37

NS-EN 12512 (2002)

Table D24: Values for HSTs calculated from NS-EN 12512(2002). Yield point method is the 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HST1s	11,41	10,72	20,0	6,49	1,79	3,63	11,17
HST2s	11,87	10,95	17,2	8,69	4,90	1,77	3,52
HST3s	12,84	12,54	18,2	9,23	3,77	2,45	4,82
HST4s	11,40	11,00	15,9	7,19	2,79	2,58	5,69
HST5s	11,62	11,12	19,8	5,90	1,68	3,51	11,77
HST6s	10,77	10,43	11,4	5,05	2,24	2,26	5,11
HST7s	11,14	10,77	12,6	4,44	1,83	2,43	6,91
HST8s	11,29	10,59	16,4	4,88	1,91	2,56	8,60
Mean Values	11,54	11,01	16,4	6,48	2,61	2,65	7,20
Standard Deviations	0,62	0,65	3,10	1,78	1,16	0,62	3,04

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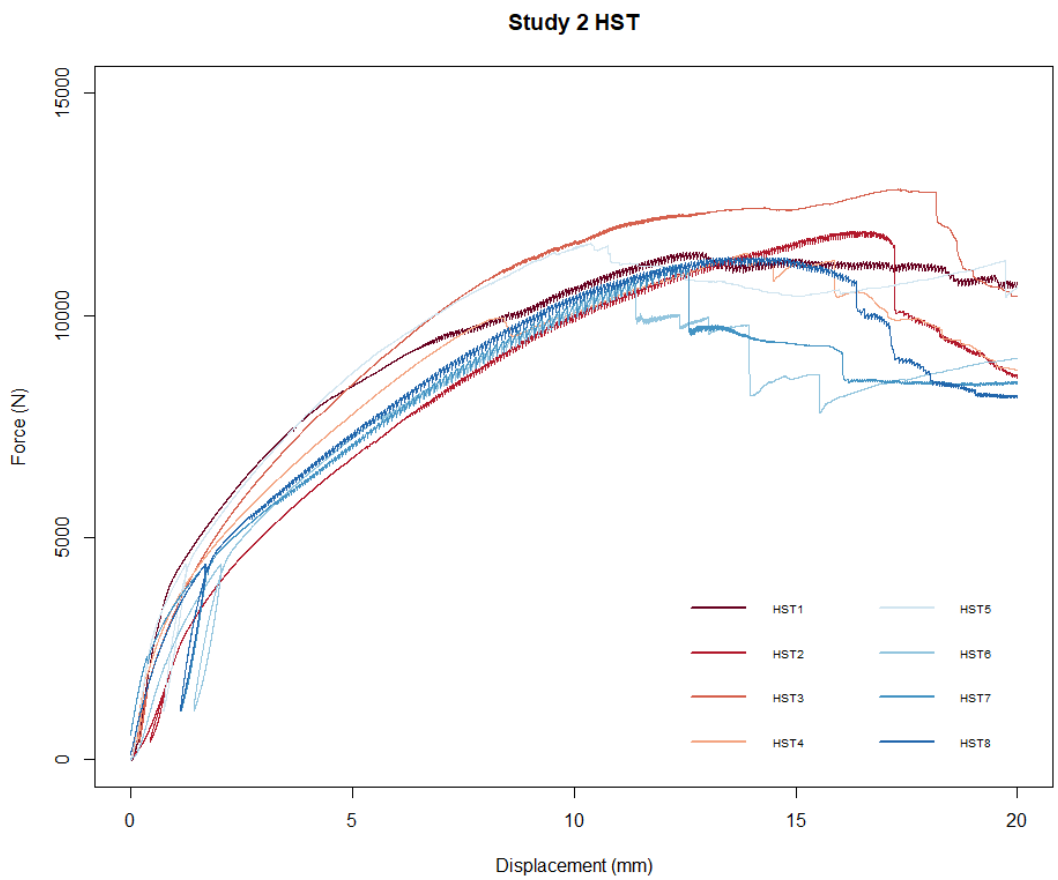
Table D25: Values for HSTs from EN 1251(2018). Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
HST1s	11,41	11,41	9,13	19,6	10,05	2,80	3,53	6,99
HST2s	11,87	11,87	11,23	17,2	9,96	5,67	1,74	3,03
HST3s	12,84	12,84	12,69	18,2	11,25	4,68	2,27	3,89
HST4s	11,40	11,40	11,13	15,8	9,66	3,87	2,33	4,09
HST5s	11,62	11,62	11,03	19,7	10,18	2,52	5,07	7,82
HST6s	10,77	10,77	10,56	11,4	8,45	3,92	2,12	2,90
HST7s	11,14	11,14	10,81	12,6	8,81	4,09	1,92	3,07
HST8s	11,29	11,29	10,55	16,4	9,60	2,88	4,86	5,69
Mean Values	11,54	11,54	10,89	16,4	9,75	3,80	2,98	4,69
Standard Deviations	0,62	0,62	0,98	3,05	0,86	1,06	1,34	1,91



Appendix E – Study 3

Moisture Content

Moisture content measured with moisturemeter for every specimen in each test group for study 3.

Table E1. Moisture content in specimens for Study 3.

specimen	Moisture Content % TW element 1|2|3||1|2|3	specimen	Moisture Content % TW element 1|2|3||1|2|3
WF-1s	14,1|12,2|11,8||13,6|12,4|12,2	WoF-1s	13,0|11,6|13,3||13,8|13,6|13,4
WF-2s	10,9|11,3|14,4||11,9|12,9|12,4	WoF-2s	13,0|11,5|12,6||12,7|11,4|13,7
WF-3s	12,4|12,1|14,0||12,4|12,7|11,8	WoF-3s	13,3|11,8|12,1||12,7|12,0|12,2
WF-4s	13,0|12,1|12,0||13,2|12,6|12,4	WoF-4s	12,2|12,2|13,2||12,6|12,3|12,4
WF-5s	12,6|12,6|14,4||12,6|12,8|12,6	WoF-5s	12,6|12,1|12,2||12,6|12,0|12,4

WFs

NS-ISO 6891 (1991)

Table E2: Values from NS-ISO 6891 (1991) calculations. Yield point method follows ISO-procedure.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
WF1	25,62	7.56	0.38	15,18
WF2	27,15	6,00	0.56	10,26
WF3	27,01	6.51	0.50	14,31
WF4	27,01	8.37	0.49	41,24
WF5	21,69	8.09	0.61	17,45
Mean Values	25,70	7.31	0.51	19,69
Standard Deviations	2,33	1.02	0.09	12,33

NS-EN 12512 (2002)

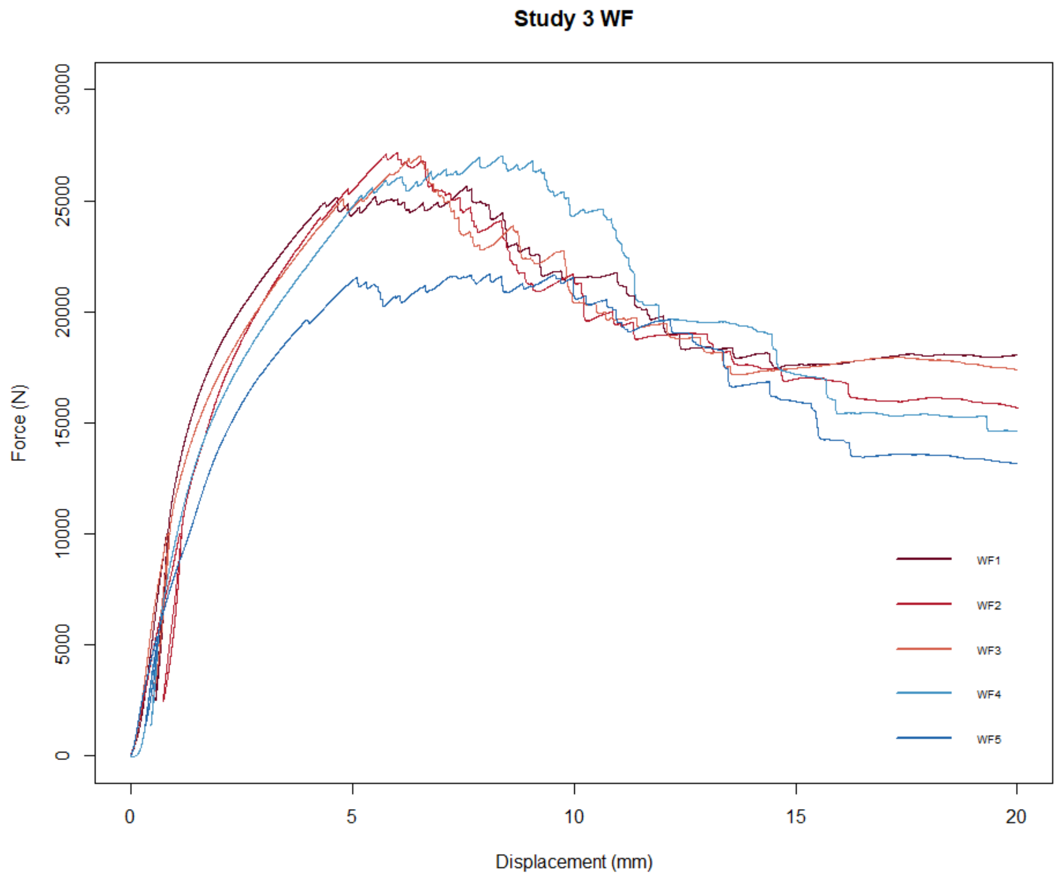
Table E3: Values from NS-EN 12512 (2002) calculations. Yield point method follows 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
WF1	25,62	20,50	11,4	13,89	0,99	14,04	11,49
WF2	27,15	21,72	8,9	16,00	1,48	10,80	6,00
WF3	27,01	17,39	20,0	14,36	1,10	13,00	18,10
WF4	27,01	14,64	20,0	17,31	1,64	10,59	12,22
WF5	21,69	17,35	13,5	16,39	1,92	8,54	7,02
Mean Values	25,70	18,32	14,7	15,59	1,43	11,39	10,97
Standard Deviations	2,33	2,81	5,06	1,43	0,38	2,16	4,82

EN 12512 (2018) Draft Version n°20180410

Table E4: Values from EN 12512 (2018) Draft proposal. Yield point method follows the EEEP curve procedure.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)	Ductility
WF1	25,62	25,62	20,50	11,4	22,78	1,31	26,97	8,65
WF2	27,15	27,15	21,72	8,9	23,64	1,88	18,76	4,74
WF3	27,01	27,01	21,61	9,8	22,84	1,52	20,15	6,47
WF4	27,01	27,01	21,61	11,4	23,83	2,29	11,33	4,97
WF5	21,69	21,69	17,35	13,5	19,84	2,23	9,72	6,04
Mean Values	25,70	25,70	20,56	11,0	22,59	1,84	17,39	6,17
Standard Deviations	2,33	2,33	1,86	1,75	1,61	0,43	7,01	1,56



WOFs

NS-ISO 6891 (1991)

Table E5: Values for WOFs calculated from NS-ISO 6891 (1991). Yield point method from Yasumura & Kawai.

	Maximum Force (kN)	Displacement at max force (mm)	Yield slip (mm)	Slip modulus (kN/mm)
WOF1	1,96	0,43	0,43	4,59
WOF2	3,79	4,91	2,26	1,65
WOF3	3,86	2,41	3,07	1,26
WOF4	2,82	14,35	1,54	1,61
WOF5	2,20	14,12	1,55	1,29
Mean Values	2,93	7,24	1,77	2,08
Standard Deviations	0,88	6,58	0,98	1,41

NS-EN 12512 (2002)

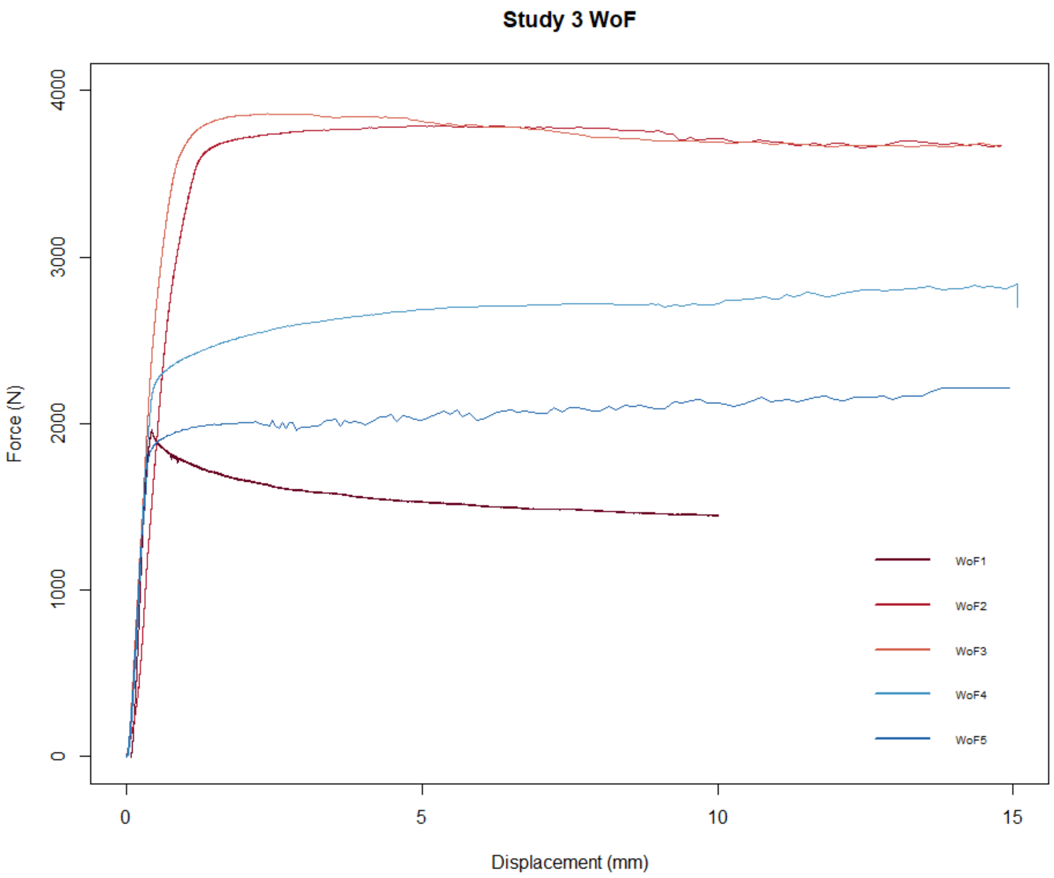
Table E6: Values for WOFs calculated from NS-EN 12512 (2002). Yield point method is 1/6 procedure.

	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
WOF1	1,96	1,57	3,8	1,80	0,35	5,15
WOF2	3,79	3,03	12,0	3,21	0,78	4,14
WOF3	3,86	3,09	13,3	3,25	0,56	5,84
WOF4	2,82	2,25	14,5	2,14	0,39	5,43
WOF5	2,20	2,20	14,1	1,74	0,33	5,30
Mean Values	2,93	2,43	11,5	2,43	0,48	5,17
Standard Deviations	0,88	0,64	4,44	0,75	0,19	0,63

EN 12512 (2018) Draft Version n°20180410

Table E7: Values for WOFs calculated from EN 12512(2018) Draft proposal. Yield point method is the EEEP curve.

	Peak Load (kN)	Maximum Force (kN)	Ultimate load (kN)	Ultimate slip (mm)	Yield load (kN)	Yield slip (mm)	Slip modulus (kN/mm)
WOF1	1,96	1,96	1,57	3,8	1,68	0,33	7,27
WOF2	3,79	3,79	3,03	12,0	3,72	0,88	4,88
WOF3	3,86	3,86	3,09	13,3	3,74	0,63	6,27
WOF4	2,82	2,82	2,25	14,5	2,68	0,48	6,41
WOF5	2,20	2,20	2,20	14,1	2,07	0,38	5,97
Mean Values	2,93	2,93	2,43	11,5	2,78	0,54	6,16
Standard Deviations	0,88	0,88	0,64	4,44	0,94	0,22	0,86


Study 3 WoF
Force (N)
0
1000
2000
3000
4000
Displacement (mm)
0
5
10
15
WoF1
WoF2
WoF3
WoF4
WoF5

Appendix F – R Script

Casagrande's dataset

```
# R SCRIPT
# Graphs, calculations and results. Calculations follows draft proposal
EN 12512 version 20180410.

# NOTE
# The script uses locator() function to manually plot out maximum points
for LEC1 and LEC3.
# It is important to locate the points in the beginning at the graph
where x=0, when using the locator.

# PACKAGES
#install.packages("gplots")
library("gplots", lib.loc="~/R/win-library/3.5")
#install.packages("ggplot2")
library("ggplot2")
# install.packages("zoo")
library("zoo")
library("stats", lib.loc="C:/Program Files/R/R-3.5.0/library")
# install.packages("xlsx")
library("xlsx", lib.loc="~/R/win-library/3.5")
library("dplyr", lib.loc="~/R/win-library/3.5")


# DATA SET INFO
specimen_name <- "90SC10mm_C_001[1153]"
study <- "TEST - Casagrande"
file_type <- ".txt"
# Reads files:
myFiles <- list.files("C:/Users/Caroline/OneDrive - Norwegian University
of Life Sciences/Master 2018/3 - DATA ANALYZING/Casagrande dataset",
                      pattern = (paste("*",file_type,sep="")))
setwd("C:/Users/Caroline/OneDrive - Norwegian University of Life
Sciences/Master 2018/3 - DATA ANALYZING/Casagrande dataset")

# creating lists etc
all_data <- c()
myFiles2 <- sub("-","",x = myFiles)
myFiles2 <- sub(".txt","",myFiles2)
result <- as.data.frame(matrix(nrow=0,ncol=length(myFiles)))
colnames(result)<-myFiles2
Final_resultsCOMP <-
as.data.frame(matrix(nrow=length(myFiles2)+2,ncol=0))
Final_resultsTENS <-
as.data.frame(matrix(nrow=length(myFiles2)+2,ncol=0))
Final_resultsSPEC <-
as.data.frame(matrix(nrow=length(myFiles2)+2,ncol=0))
rownames(Final_resultsCOMP)<-c(myFiles2,"Mean Values","Standard
Deviations")
rownames(Final_resultsTENS)<-c(myFiles2,"Mean Values","Standard
Deviations")
rownames(Final_resultsSPEC)<-c(myFiles2,"Mean Values","Standard
Deviations")
beta <- intToUtf8(946)
```

```
v_eq_values <- c()

# Stores dataset in list tables named dat. for-loop if there are several
datasets.
for (i in 1:length(myFiles)){
  dat <- read.table(myFiles[i],sep="",dec=".",header=TRUE)
  result["max load(N)",i] <- max(dat$`Force`)
  row1 <- which.max(dat$`Force`)
  result["max displ(mm)",i] <- dat[row1,2]
  all_data[[i]] <- dat
}
names(all_data)<-myFiles


# CALCULATIONS ON DATASET
for (i in 1:length(all_data)){ # If several data set is present
  name_specimen <- paste(specimen_name,i,sep = "")
  main_title <- paste(study," - ", specimen_name,i,sep = "")
  specimen <- as.data.frame(all_data[[i]])
  specimen$lopende_kraft<-NA
  # smoothing the force
  for (p in 10:(nrow(specimen)-1)){

    linje<-p+1
    intervall<-c(linje-10,linje+10)
    specimen$lopende_kraft[linje]<-
mean(specimen[intervall[1]:intervall[2],3])
  }

  specimen <- specimen[complete.cases(specimen), ]
  my_data <- data.frame(matrix(nrow=0,ncol=3))
  my_data <- specimen[1] #time
  my_data[2] <- specimen[2] #displacement
  my_data[3] <- specimen[3] # [3]=NO force smoothed, [4]=force smoothing
  colnames(my_data)<-c("Time", "Position","Force (smoothed)")
  # NOTE: smoothing value should be changed after raw data properties.
  # For experiment done at NMBU on Instron machine, the raw data are
often big and noisy.
  # Meaning that force smoothing is needed.
  # For casagrande's dataset no smoothing was needed.


  # -----------------------------------------------------------------
  # ENVELOPE CURVE
  # locating manually with locator() function with nine points for each
LEC in tension and compression.
  # Start by locating from the cycleset with three cycles.

  #LEC1 Tension coordinates
  LEC1_TENS <- as.data.frame(matrix(nrow = 0,ncol = 2))
  subse <- subset(my_data,my_data$Position > 0)
  plot(subse$Position,subse$`Force (smoothed)`,type = "l",
       main = main_title, col = "Orange",cex = 0.2,
       xlab = "Displacement (mm)",ylab = "Force (N)")
  for (k in 1:9) {
    coord_TENS <- locator(1)
    if (!is.null(coord_TENS)) {
      LEC1_TENS[k,1] <- coord_TENS$x
      LEC1_TENS[k,2] <- coord_TENS$y
    }
  }
```

```
LEC1_TENS <- rbind(c(0,0),LEC1_TENS)

#LEC3 Tension coordinates
LEC3_TENS <- as.data.frame(matrix(nrow = 0,ncol = 2))
subse <- subset(my_data,my_data$Position > 0)
plot(subse$Position,subse$`Force (smoothed)`,type = "l",
     main = main_title, col = "Orange",cex = 0.2,
     xlab = "Displacement (mm)",ylab = "Force (N)")
for (k in 1:9) {
  coord_TENS <- locator(1)
  if (!is.null(coord_TENS)) {
    LEC3_TENS[k,1] <- coord_TENS$x
    LEC3_TENS[k,2] <- coord_TENS$y
  }
}
LEC3_TENS <- rbind(c(0,0),LEC3_TENS)

#LEC1 Compression coordinates
LEC1_COMP <- as.data.frame(matrix(nrow = 0,ncol = 2))
subse <- subset(my_data,my_data$Position < 0)
plot(subse$Position,subse$`Force (smoothed)`,type = "l",
     main = main_title, col = "Orange",cex = 0.2,
     xlab = "Displacement (mm)",ylab = "Force (N)")
for (k in 1:9) {
  coord_COMP <- locator(1)
  if (!is.null(coord_TENS)) {
    LEC1_COMP[k,1] <- coord_COMP$x
    LEC1_COMP[k,2] <- coord_COMP$y
  }
}
LEC1_COMP <- rbind(c(0,0),LEC1_COMP)

#LEC3 Compression coordinates
LEC3_COMP <- as.data.frame(matrix(nrow = 0,ncol = 2))
subse <- subset(my_data,my_data$Position < 0)
plot(subse$Position,subse$`Force (smoothed)`,type = "l",
     main = main_title, col = "Orange",cex = 0.2,
     xlab = "Displacement (mm)",ylab = "Force (N)")
for (k in 1:9) {
  coord_COMP <- locator(1)
  if (!is.null(coord_COMP)) {
    LEC3_COMP[k,1] <- coord_COMP$x
    LEC3_COMP[k,2] <- coord_COMP$y
  }
}
LEC3_COMP <- rbind(c(0,0),LEC3_COMP)


# interpolating LEC1 and LEC3
 LEC1_COMP <- as.data.frame(approx(LEC1_COMP[[1]],LEC1_COMP[[2]],
    method = "linear", n = 1000)) #interpolation
LEC1_TENS <- as.data.frame(approx(LEC1_TENS[[1]],LEC1_TENS[[2]],
    method = "linear", n = 1000))
LEC3_COMP <- as.data.frame(approx(LEC3_COMP[[1]],LEC3_COMP[[2]],
    method = "linear", n = 1000)) #interpolation
LEC3_TENS <- as.data.frame(approx(LEC3_TENS[[1]],LEC3_TENS[[2]],
    method = "linear", n = 1000))
colnames(LEC1_COMP) <- c("Position","Force")
colnames(LEC1_TENS) <- c("Position","Force")
names(LEC3_COMP) <- c("Position","Force")
names(LEC3_TENS) <- c("Position","Force")
```

```
  # limiting the decimals to two digits, so that it is possible to
divide with correct displacements.
  is.num <- sapply(LEC1_TENS, is.numeric)
  LEC1_TENS[is.num] <- lapply(LEC1_TENS[is.num], round, 2)
  is.num <- sapply(LEC3_TENS, is.numeric)
  LEC3_TENS[is.num] <- lapply(LEC3_TENS[is.num], round, 2)
  is.num <- sapply(LEC1_COMP, is.numeric)
  LEC1_COMP[is.num] <- lapply(LEC1_COMP[is.num], round, 2)
  is.num <- sapply(LEC3_COMP, is.numeric)
  LEC3_COMP[is.num] <- lapply(LEC3_COMP[is.num], round, 2)

  #-------------------------------------------------------------------

  # CALCULATION | Ultimate load (Failure; 80% Pl_max, Delta_F):
  # Failure is not calculated due to no distinct failure-drop in these
experiments LECs.

  # PEAK LOAD (Pl) IN LEC1, COMPRESSION
  row1 <- which.min(LEC1_COMP$Force)
  Pl_COMP <- LEC1_COMP$Force[row1]
  V_Pl_COMP <- LEC1_COMP$Position[row1]

  # PEAK LOAD (Pl) IN LEC1, TENSION
  row2 <- which.max(LEC1_TENS$Force)
  Pl_TENS <- LEC1_TENS$Force[row2]
  V_Pl_TENS <- LEC1_TENS$Position[row2]

  result["Peak Load Compression (N)", i] <- Pl_COMP
  result["Displ at Peak Load compression (mm)",i] <- V_Pl_COMP
  result["Peak Load Tension (N)", i] <- Pl_TENS
  result["Displ at Peak Load Tension (mm)",i] <- V_Pl_TENS

  # DISPLACEMENT 80% Pl_max after peak load, COMPRESSION
  Pl_80_COMP <- 0.8*Pl_COMP
  subs <- subset(LEC1_COMP,LEC1_COMP$Position < V_Pl_COMP)
  row <- which.min(abs(subs$Force - Pl_80_COMP))
  V_Pl80_COMP <- subs$Position[row]
  result["80% Peak Load Compression (N)",i] <- Pl_80_COMP
  result["Displ at 80% Peak Load Compression (mm)",i] <- V_Pl80_COMP

  # DISPLACEMENT 80% Pl_max after peak load, TENSION
  Pl_80_TENS <- 0.8*Pl_TENS
  subs <- subset(LEC1_TENS,LEC1_TENS$Position > V_Pl_TENS)
  row <- which.min(abs(subs$Force - Pl_80_TENS))
  V_Pl80_TENS <- subs$Position[row]
  result["80% Peak Load  Tension (N)",i] <- Pl_80_TENS
  result["Displ at 80% Peak Load Tension (mm)",i] <- V_Pl80_TENS

  #---------------------------------------------------
  # STRENGTH DEGRADATION FACTOR BETWEEN LEC1 AND LEC3
  beta_min <- 0.75 # A given beta_min

  # Compression
  # Firstly, need to make a new data-frame, d12, where LEC1 and LEC3 are
      joined with the same displacements.
  # Secondly dividing the force that matches the same displacements and
      binding them to a new data-frame Beta_COMP.
  df12 <- left_join(LEC1_COMP, LEC3_COMP, by = 'Position')
  beta_COMP <- cbind(df12[1], df12[3] / df12[2])
  beta_COMP <- beta_COMP[beta_COMP$Force.y < 1,]
```

```
beta_COMP <- beta_COMP[complete.cases(beta_COMP), ]
beta_COMP <-
    as.data.frame(approx(beta_COMP$Position,beta_COMP$Force.y,
          method = "linear", n = 500)) #interpolation
colnames(beta_COMP) <- c("Position","Force.y")

# plot(beta_COMP$Position,beta_COMP$Force,type = "l")

# Tension
# Firstly, need to make a new data-frame, d12, where LEC1 and LEC3 are
    joined after the same positions.
# Secondly dividing the force that matches the same position and
    binding them to a new data-frame Beta_TENS.
df12 <- left_join(LEC1_TENS, LEC3_TENS, by = 'Position')
beta_TENS <- cbind(df12[1], df12[3] / df12[2])
beta_TENS <- beta_TENS[beta_TENS$Force.y < 1,]
beta_TENS <- beta_TENS[complete.cases(beta_TENS), ]
beta_TENS <-
    as.data.frame(approx(beta_TENS$Position,beta_TENS$Force,
          method = "linear", n = 500))
colnames(beta_TENS) <- c("Position","Force.y")

# plot(beta_TENS$Position,beta_TENS$Force,type = "l")

# checking if beta is valid as ultimate displacement
# tension
rowT <- which.min(beta_TENS$Force.y)
betaMinValue_T <- beta_TENS$Force.y[rowT]
if (betaMinValue_T <= beta_min) {
#if BetaMinValue_T is lower than beta_min it is valid as an ultimate
    Displacement.
  sub_beta_T <- subset(beta_TENS,
                beta_TENS$Position < beta_TENS$Position[rowT])
  rowTT <- which.min(abs(sub_beta_T$Force.y - beta_min))
  V_beta_TENS <- sub_beta_T$Position[rowTT]
  row_Fbeta <- which.min(abs(LEC1_TENS$Position - V_beta_TENS))
  F_beta_TENS <- LEC1_TENS$Force[row_Fbeta]
} else { # if not, it is ignored when deciding ultimate displacement.
  V_beta_TENS <- NA
  F_beta_TENS <- NA
}
# compression
rowC <- which.min(beta_COMP$Force.y)
betaMinValue_C <- beta_COMP$Force.y[rowC]
if (betaMinValue_C <= beta_min) {
  #if BetaMinValue_T is lower than beta_min it is valid as an ultimate
          displacement
  sub_beta_C <- subset(beta_COMP,
                beta_COMP$Position >= beta_COMP$Position[rowC])
  rowCC <- which.min(abs(sub_beta_C$Force.y - beta_min))
  V_beta_COMP <- sub_beta_C$Position[rowCC]
  row_Fbeta <- which.min(abs(LEC1_COMP$Position - V_beta_COMP))
  F_beta_COMP <- LEC1_COMP$Force[row_Fbeta]
} else { # if not, it is ignored when deciding ultimate displacement.
  V_beta_COMP <- NA
  F_beta_COMP <- NA
}

result["Degradation Load Compression (N)",i] <- F_beta_COMP
result["Degradation Displ Compression (mm)",i] <- V_beta_COMP
result["Degradation Load Tension (N)",i] <- F_beta_TENS
```

```
result["Degradation Displ Tension (mm)",i] <- V_beta_TENS
#------------------------------------------------------------------------

# FINAL ULTIMATE LOAD
# Deciding the displacement that occurs first.
Displ_Values_COMP <- c(V_P180_COMP,V_beta_COMP)
Load_Values_COMP <- c(Pl_80_COMP,F_beta_COMP)
mini_COMP <- which.max(Displ_Values_COMP)
Ultimate_displ_COMP <- Displ_Values_COMP[mini_COMP]
Ultimate_force_COMP <- Load_Values_COMP[mini_COMP]

Displ_Values_TENS <- c(V_P180_TENS,V_beta_TENS)
Load_Values_TENS <- c(Pl_80_TENS,F_beta_TENS)
mini_TENS <- which.min(Displ_Values_TENS)
Ultimate_displ_TENS <- Displ_Values_TENS[mini_TENS]
Ultimate_force_TENS <- Load_Values_TENS[mini_TENS]

result["Ultimate Force Compression (N)",i] <- Ultimate_force_COMP
result["Ultimate Displ Compression (mm)",i] <- Ultimate_displ_COMP
result["Ultimate Force Tension (N)",i] <- Ultimate_force_TENS
result["Ultimate Displ Tension (mm)",i] <- Ultimate_displ_TENS

# MAXIMUM LOAD - equal to or lower than the ultimate displacement
# COMPRESSION
sub_Fmax_C <- subset(LEC1_COMP,
                LEC1_COMP$Position >= Ultimate_displ_COMP)
rowmaxC <- which.min(sub_Fmax_C$Force)
F_maxC <- sub_Fmax_C[rowmaxC,2]

# TENSION
sub_Fmax_T <- subset(LEC1_TENS,
                LEC1_TENS$Position <= Ultimate_displ_TENS)
rowmaxT <- which.max(sub_Fmax_T$Force)
F_maxT <- sub_Fmax_T[rowmaxT,2]

#------------------------------------------------------------------------
# PLOTTING GRAPH
plot(my_data$Position,my_data$`Force (smoothed)`,type = "l",
          main = main_title, col = "Orange",cex = 0.2,
          xlab = "Displacement (mm)",ylab = "Force (N)")

# plotting 1st LEC
points(LEC1_COMP, cex=0.2,col="Black",type="l")
points(LEC1_TENS, cex=0.2,col="Black",type="l")
# plotting 3rd LEC
points(LEC3_COMP, cex=0.2,col="Blue",type="l")
points(LEC3_TENS, cex=0.2,col="Blue",type="l")

# plotting ultimate displ
abline (v=Ultimate_displ_COMP,col="grey", lty = 2, lwd = 1,
          pch = 3, lend = 0, ljoin = 2)
abline (v=Ultimate_displ_TENS,col="grey", lty = 2, lwd = 1,
          pch = 3, lend = 0, ljoin = 2)
text(Ultimate_displ_TENS+0.1,Pl_COMP,labels = "Vu",adj = c(0,0),
          cex = 0.8, col = "grey")
text(Ultimate_displ_COMP+0.1,Pl_COMP,labels = "Vu",adj = c(0,0),
          cex = 0.8, col = "grey")

# plotting only the positive LECs
main_title2 <- paste("Envelope curve LEC1 and LEC3 - ",
                specimen_name,i,sep="")
```

```
plot(LEC1_TENS, type = "l", col = "Black", main = main_title2 )
points(LEC3_TENS, type = "l", col = "Lightblue", cex = 0.2)
points(LEC1_TENS, type = "l", col = "Black")
# plotting ultimate displ and force
abline (v=Ultimate_displ_TENS,col="Black", lty = 2, lwd = 1,
          pch = 3, lend = 0, ljoin = 2)
text(Ultimate_displ_TENS+0.1,20,labels = "Vu",adj = c(0,0),
          cex = 0.8, col = "Black")

#----------------------------------------------------------------------
---------------------------------
# CALCULATING THE EEEP CURVE

# First, we retrieve the area under the LEC1 curve.
# AUC is the area under the curve with boundaries from origin to
    ultimate displacement
xsub <- subset(LEC1_TENS,LEC1_TENS$Position <= Ultimate_displ_TENS)
x <- xsub$Position
y <- xsub$Force
id <- order(x)
AUC <- sum(diff(x[id])*rollmean(y[id],2))

# Finding the line that goes through 10%Fmax and 40%Fmax ~ line1
row3 <- which.min(abs(xsub$Force - (0.1*F_maxT)))
V10 <- xsub[row3,1]
F10 <- xsub[row3,2]
row4 <- which.min(abs(xsub$Force - (0.4*F_maxT)))
V40 <- xsub[row4,1]
F40 <- xsub[row4,2]
xcoord <- c(V10,V40)
ycoord <- c(F10,F40)

# plotting points and slope in LEC graph
points(x = V10, y = F10,col="Red")
points(x = V40, y=F40, col="Red")
fit <- lm(ycoord~xcoord)
abline(fit, col="black",lty = 2, lwd = 1, pch = 3,
          lend = 0, ljoin = 2)

# The intercept and slope for line1 is found and so are the elastic
    stiffness which is equal to the slope.
b <- coef(lm(ycoord~xcoord))[1] #intercept
a <- coef(lm(ycoord~xcoord))[2] #slope
K <- a[[1]] # Elastic stiffness [N/mm]
Vu <- Ultimate_displ_TENS # ultimate displacement

# the equation to find the horisontal line (line2) that gives an EEEP
    area equal to the LEC1 area is an quadratic equation.
# The y-solution to the line is then given as plus and minus,
    referring to the quadratic formula. Minus is for the
# tension side and plus is for the compression side.

mMinus = a[[1]]*((Vu+b[[1]]/a[[1]]) -
    sqrt((Vu+b[[1]]/a[[1]])^2 - 4*((b[[1]]/(4*a[[1]]))^2 +
    AUC/(2*a[[1]])))) #with x=0 as initial boundary

# the intersection is the yield load and displacement.
F_y <- mMinus
v_y <- (mMinus - b[[1]])/a[[1]]
result["v_y",i] <- v_y
result["F_y",i] <- F_y
```

```
# drawing the yield load and displacement lines into the graph
abline(h = F_y, col="grey",lty = 2, lwd = 1, pch = 3,
          lend = 0, ljoin = 2)
abline(v = v_y, col="grey",lty = 2, lwd = 1, pch = 3,
          lend = 0, ljoin = 2)
#----------------------------------------------------------------------

# DUCTILITY, D_c
D_c <- Ultimate_displ_TENS/v_y
result["D_c",i] <- D_c

# DESIGN STRENGTH DEGRADATION FACTOR, Beta_sd
# The strength degradation factor shall ble calculated for values of
    displacement lower than the ultimate displacement.
# We then need to subset the values that are lower than Vu.

# COMPRESSION
beta_sub <- subset(beta_COMP,beta_COMP$Position > Ultimate_displ_COMP)
row5 <- which.min(beta_sub$Force.y)
beta_sd_COMP <- beta_sub$Force.y[row5] # minimum value of beta in this
    interval
# If beta_sd is lower than beta_min, then beta_sd should be set equal
    to beta_min. EN 12512 - 3.18 (V.20180410)
if (beta_sd_COMP < beta_min) {
  beta_sd_COMP <- beta_min
}

# TENSION
beta_sub_T <- subset(beta_TENS,
                beta_TENS$Position < Ultimate_displ_TENS)
row6 <- which.min(beta_sub_T$Force.y)
beta_sd_TENS <- beta_sub_T$Force.y[row6] # minimum value of beta in
    this interval
if (beta_sd_TENS < beta_min) {
  beta_sd_TENS <- beta_min
}

result["beta_sd_COMP",i] <- beta_sd_COMP
result["beta_sd_TENS",i] <- beta_sd_TENS

#----------------------------------------------------------------------
# FINAL RESULTS TABLE

# Compression
Final_resultsCOMP[i,"Peak Load (N)"] <- Pl_COMP
Final_resultsCOMP[i,"Displacement at Peak Load (mm)"] <- V_Pl_COMP
Final_resultsCOMP[i,"Maximum Load (N)"] <- F_maxC
Final_resultsCOMP[i,"Ultimate displacement (mm)"] <-
                Ultimate_displ_COMP
Final_resultsCOMP[i,paste0("Design Strength Degradation factor - ",
                beta,"_sd")] <- beta_sd_COMP

# Tension
Final_resultsTENS[i,"Peak Load (N)"] <- Pl_TENS
Final_resultsTENS[i,"Displacement at Peak Load (mm)"] <- V_Pl_TENS
Final_resultsTENS[i,"Maximum Load (N)"] <- F_maxT
Final_resultsTENS[i,"Ultimate displacement (mm)"] <-
                Ultimate_displ_TENS
Final_resultsTENS[i,paste0("Design Strength Degradation Factor - ",
                beta,"_sd")] <- beta_sd_TENS
```

```
Final_resultsSPEC[i,"Yield slip (mm) - v_y"] <- v_y
Final_resultsSPEC[i,"Yield load (N) - F_y"] <- F_y
Final_resultsSPEC[i,"Slip modulus - k_ser (N/mm)"] <- K
Final_resultsSPEC[i,"Static ductility - D"] <- D_c


# SAVING PLOTS
png_name <- paste("Graph_",name_specimen,sep="")
png(file=paste(png_name,".png",sep=""),width=5, height=5,
          units="in", res=200)

par(mfrow = c(2,1))
par(mar=c(3,3,1.5,1),mgp = c(1.2,0.35,0))
# plotting graph in saver
plot(my_data$Position,my_data$`Force (smoothed)`,type = "l",
          col = "gray60",cex = 0.2,lwd = 0.5,
          xlab = "Displacement (mm)",ylab = "Force (N)",
          cex.lab = 0.65, cex.axis = 0.55)
title(main_title, cex.main = 0.75, line = 0.5 )

# plotting 3rd LEC
points(LEC3_COMP, cex=0.2,col="sienna3",type="l")
points(LEC3_TENS, cex=0.2,col="sienna3",type="l")
# plotting 1st LEC
points(LEC1_COMP, cex=0.2,col="Black",type="l")
points(LEC1_TENS, cex=0.2,col="Black",type="l")


# plotting ultimate displ and force
abline (v=Ultimate_displ_COMP,col="grey80", lty = 2, lwd = 0.8,
          pch = 3, lend = 0, ljoin = 2)
abline (v=Ultimate_displ_TENS,col="grey80", lty = 2, lwd = 0.8,
          pch = 3, lend = 0, ljoin = 2)
text(Ultimate_displ_TENS-0.1,Pl_COMP,
          labels = expression(paste("V"["u"])),adj = c(1,0.75),
          cex = 0.5, col = "grey60")
text(Ultimate_displ_COMP+0.1,Pl_COMP,
          labels = expression(paste("V"["u"])),adj = c(0,0.75),
          cex = 0.5, col = "grey60")
legend("bottomright",c("Load-Displacement\ncyclic curve",
          expression(paste("1"^"st"," envelope curve - LEC1")),
          expression(paste("3"^"rd"," envelope curve - LEC3"))),
          lty=1,lwd = 1, cex = 0.4, box.lty = 0,inset =  0.001,
          box.lwd = 0.8,col = c("gray60","black","sienna3"))

# plotting only the positive LECs
EEEP_LEC1_subset <- subset(LEC1_TENS,
          LEC1_TENS$Position<=Ultimate_displ_TENS)
EEEP_LEC3_subset <- subset(LEC3_TENS,
          LEC3_TENS$Position<=Ultimate_displ_TENS+0.1)
main_title2 <- paste("EEEP Curve - ", specimen_name,i,sep="")
plot(EEEP_LEC1_subset, type = "l", col = "Black",
          xlab = "Displacement (mm)",ylab = "Force (N)",
          cex.lab = 0.65, cex.axis = 0.55)
title(main_title2, cex.main = 0.75, line = 0.5)
points(EEEP_LEC3_subset, type = "l", col = "antiquewhite2", cex = 0.2)
points(EEEP_LEC1_subset, type = "l", col = "Black", cex = 0.2)
# plotting ultimate displ and force
abline (v=Ultimate_displ_TENS,col="black", lty = 2, lwd = 1,
          pch = 3, lend = 0, ljoin = 2)
```

```
  text(Ultimate_displ_TENS-0.01,0,
            labels = expression(paste("V"["u"])),adj = c(1,0),
            cex = 0.5, col = "black")

  # plotting in the LEC 10% and 40% points and slope.
  points(x = V10, y = F10,col="grey60")
  points(x = V40, y=F40, col="grey60")
  fit <- lm(ycoord~xcoord)
  abline(fit, col="Brown3",lty = 2, lwd = 0.8, pch = 3,
            lend = 0, ljoin = 2)
  # plotting Fy and Vy lines
  abline(h = F_y, col="Brown3",lty = 2, lwd = 0.8, pch = 3,
            lend = 0, ljoin = 2)
  text(v_y,F_y+5, labels = expression(paste("F"["y"])),adj = c(1,0),
            cex = 0.5,col = "brown3")
  dev.off()
  #----------------------------------------------------------------------

  # Plotting displacement characterized by beta in tension. Beta <=
      beta_min
  plot(beta_TENS$Position,beta_TENS$Force.y,type = "l",main = beta,
            ylim = c(0.6,1), xlab = "Displacement (mm)",
            ylab = paste(beta,"_tension"),col = "red")
  abline(h=0.75)
  text(1,0.75,labels = "0.75", adj = c(1,1))
  abline(h=beta_sd_TENS)
  text(1,beta_sd_TENS,labels = "0.768",adj = c(1,1))
  abline(v=V_P180_TENS)
  text(V_P180_TENS,0.65,labels = "Vu = 23.8",adj = c(0,0))

}

# Restricts decimals to three numbers in the tables of interest.
is.num <- sapply(Final_resultsCOMP, is.numeric)
Final_resultsCOMP[is.num] <- lapply(Final_resultsCOMP[is.num], round, 3)
is.num <- sapply(Final_resultsTENS, is.numeric)
Final_resultsTENS[is.num] <- lapply(Final_resultsTENS[is.num], round, 3)
is.num <- sapply(Final_resultsSPEC, is.numeric)
Final_resultsSPEC[is.num] <- lapply(Final_resultsSPEC[is.num], round, 3)
is.num <- sapply(result, is.numeric)
result[is.num] <- lapply(result[is.num], round, 3)


# SAVING TABLES AS .TXT FILES IN THE SAME WORK DIRECTORY WRITTEN IN THE
TOP OF THIS SCRIPT
write.xlsx(Final_resultsCOMP, file = "Final_resultsCOMP.xlsx",
            row.names = T, col.names = T)
write.xlsx(Final_resultsTENS, file = "Final_resultsTENS.xlsx",
            row.names = T, col.names = T)
write.xlsx(Final_resultsSPEC, file = "Final_resultsParameters.xlsx",
            row.names = T, col.names = T)
```

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