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Analysis of hybrid steel – glass beam

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Preface

This Master thesis has been written at the Norwegian University of Life Science (NMBU) in the summer from May 15th to August 15th 2017.

As a student with specialization in architecture, I was intrigued when my Professor Themistoklis Tsalkatidis, presented a suggestion for a thesis about a hybrid steel-glass beam. Structural glass is a very relevant topic as the demand for transparent buildings is increasing. With no knowledge about structural glass and little experience with finite element programs, I jumped into this thesis with hope to give some understanding to the potential of the hybrid beams with glass as one of the main materials. The thesis is mainly analytical and the results presented is more of an introduction to the discussion of the potential and limits of hybrid glass beams.

The biggest challenge with this thesis has been the learning process of Ansys mechanical (APDL), however the learning curve has been steep and I have enjoyed the time required spent on the thesis.

Acknowledgements

I would like to thank my supervisor, Associate Professor Themistoklis Tsalkatidis for the support while writing the Thesis. I would also like to thank my family and friends for supporting me.

Abstract

In recent years, there has been a lot of research and development on structural glass elements. This is mainly due to the increasing amount of demand for transparent material in architecture caused by the esthetic and practical upsides with these kinds of materials. Current research implies that elements effected by considerable stresses is often not sustainable if the element consist of only glass because of its properties, in regards to tensional capacity. By combining glass elements with tensional stress-resistant materials, it is possible to make transparent beams with sufficient capacities. In this thesis, a configuration of a hybrid steel – glass beam will be analyzed to further explore the potential of structural glass. The thesis consists of 3 models: one theoretical model, one simplified Finite element model (APDL) and one more in-depth Finite element model. There will also be a discussion on how one can optimize the beam in regards to both transparency and structural capacity.

Sammendrag

De siste årene har det vært mye forskning og utvikling innen konstruksjonsglass. Grunnen er at det er en økt etterspørsel etter transparente konstruksjonselementer i arkitekturen. Dette er fordi transparente elementer har estetiske og praktiske fordeler. Glass har svak strekk-kapasitet og bjelker bestående av kun glass er derfor ikke ideelt. Ved å kombinere Glass og materialer som stål og tre, så er det mulig å dimensjonere bjelker med tilstrekkelig kapasiteter. Denne oppgaven består i hovedsak av 3 modeller; En teoretisk modell, en forenklet FE (APDL) modell og en mer omfattende FE modell (APDL). Resultatene fra disse analysene vil være basen for en diskusjon om hvordan man kan optimalisere det valgte tverrsnittet i henhold til arkitektoniske og konstruksjonsmessige forhold.

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$I_{equivalent}$ – Total moment of inertia of the beam

I_w – Moment of inertia of the web

$I_{f, upper, equivalent}$ - Moment of inertia of the upper flange

$I_{f, bottom, equivalent}$ -Moment of inertia of the lower flange

W_1 – Section of modulus of the web

W_2 – Section of modulus of the entire beam

$\sigma_{limit, glass}$ – Tensional stress capacity of glass

$\tau_{dim, glass}$ – Shear capacity of glass

δ – Deflection of the simply supported beam

E_s – Elasticity of steel

E_g – Elasticity of glass

n – Ratio between E_s and E_g

M – Occurring maximum moment with load q

q – Line load over beam length l

l – Length of the beam

h – Height of the beam

b – Width of the flange

e – Thickness of flange

T_g – Thickness of web

y, centroid – Distance to end of flange from center of mass.

1 Introduction

Glass has always been one of the traditional elements in buildings throughout history, in regards to both practical and architectural application. In modern times, glass is no longer limited to compliment the structure esthetically, but can also contribute to structural applications due to the rapid progression within the structural engineering community and the increasing demand for transparent and complex structures in architecture.

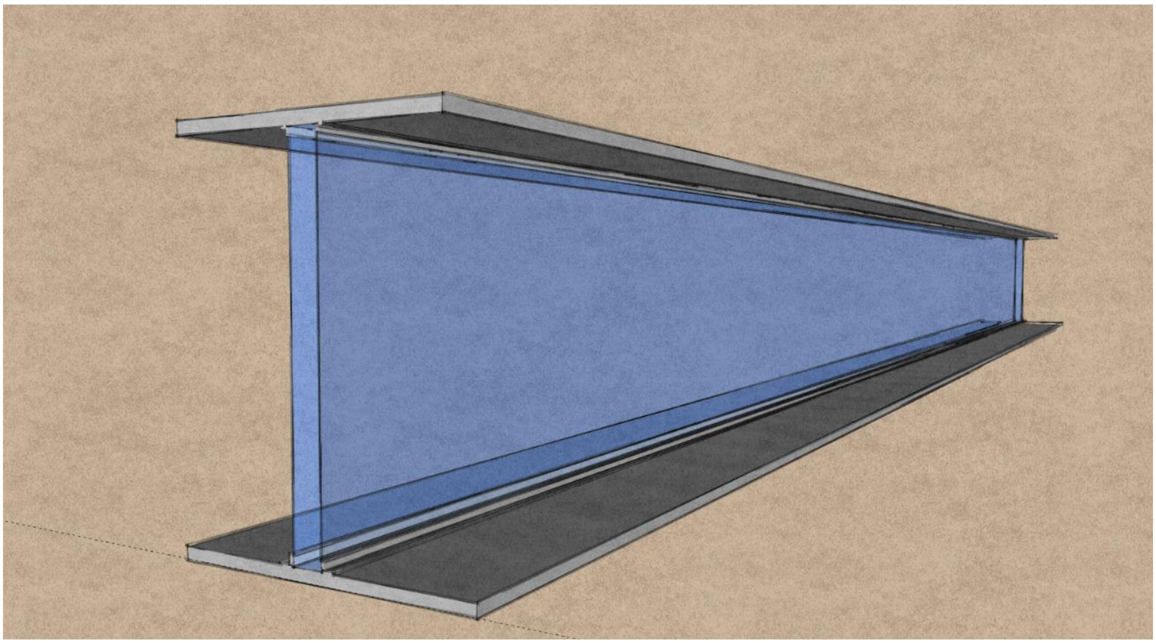


FIGURE 1 - HYBRID GLASS-STEEL BEAM CONFIGURATION

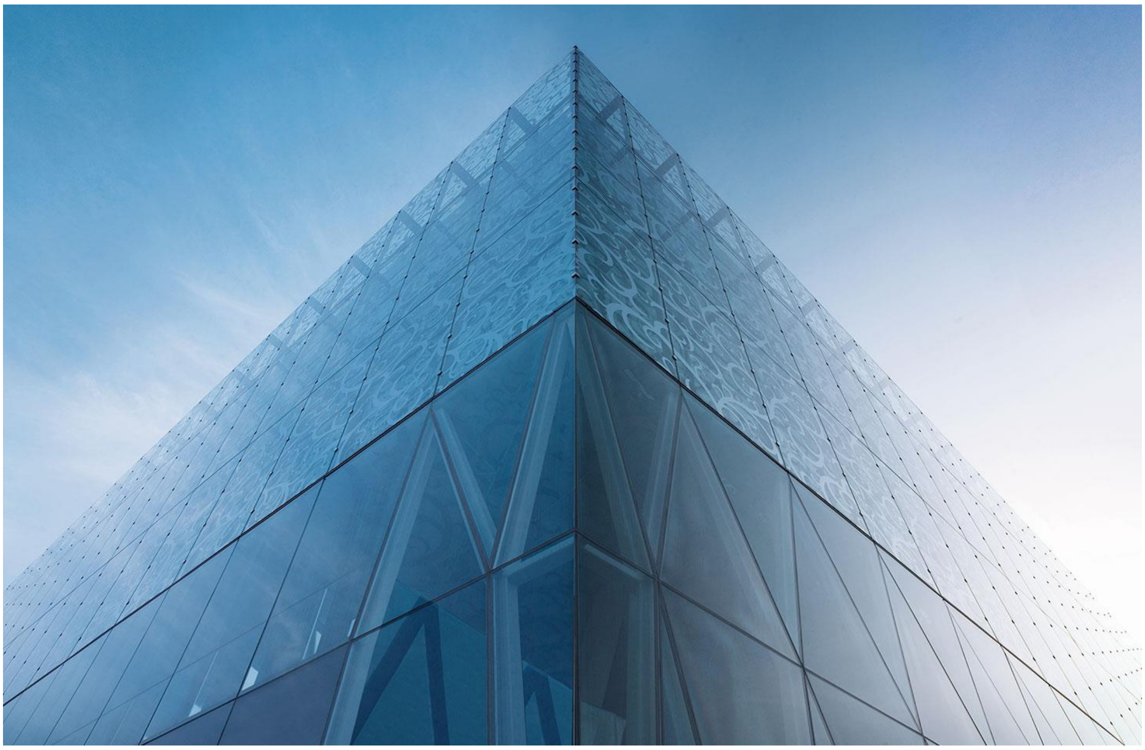


FIGURE 2 – GLASS FACADES

“The noble patterned structural glass façade on the John Lewis department store in Leicester, UK”

The impressive compressive capacity of glass makes these kinds of glass facades durable in combination with a steel frame loadbearing systems.

FIGURE 3 – TIMBER – GLASS HYBRID BEAM

Timber – glass composite beams in “Palafitte hotel” in Switzerland – Conference room

The concept was developed by Kreher and tested on a full-scale before being applied. The hybrid timber – glass beam is the main bearing element of the roof structure. This picture gives some indication to the potential of using glass with structural applications to give practical use that nontransparent elements would fail to give.

2 Theory

Glass Theory

The properties of Glass:

Glass is the isotropic, elastic material and it has no plastic phase meaning that it will break almost instantaneously when passing the elastic phase. In construction, this is of major concern, given that there are no warning when the given component/element is going to collapse. This is one of the main concerns when it comes to applying glass in structural design. Figure?

Glass have some of the same physical behavior as concrete. It is a brittle material. It has a high theoretical stress capacity, but due to imperfect surface that are next to impossible to prevent the practical capacity is much lower and therefore it is ideal to use another material in the stress focused area of a beam section. Glass has a relatively high compression capacity and a manageable shear capacity witch we can exploit in the attempt to construct the hybrid – beam.

The components of glass:

The main constituent of the standard flat glass is the SiO2 (silica sand). The basic reaction [11]:

$$Na_2CO_3 + SIO_2 \rightarrow 1500\ C \rightarrow Na_2SiO_3 + CO_2 \uparrow$$

$$Na_2SiO_3 + x^*\ SiO_2 \rightarrow \overset{(Na_2SO_4)}{\text{Digestion}} \rightarrow (Na_2O)(SiO_2)\ (x+1)$$

The main types of glass are the following [10]:

Annealed glass:

This type is the standard float glass that you see in architecture. When broken, the glass splits into large fragments. This is the standard glass type that will be considered in the models.

Fully tempered Glass:

This type is also known as toughened glass. This type is created by heating the glass then cooled at a high rate, under the tempering of the glass. The result of this method makes tensile concentration at the core of the glass and compression concentration on the surface of the glass. If the surface of the glass is exposed to stress we often get large cracks. On the other side if comparison is the net on the surface, the glass tends to break in to small harmless pieces. This is why this type is a safety glass.

Heat strengthened glass

The production of this type is based on the same concept as the previous type, but the rate at which the glass is cooled is reduced. This results in less tensile concentrations. The Heat strengthened glass therefore breaks in to larger pieces then the fully tempered glass, making it less ideal for use of safety glass. The upside with this type is that it will still have relevant capacity in the post breakage phase and this is crucial especially in the structural glass.

Laminated Glass

This type in essence is two or more glass panes bonded together with a plastic interlayer, though it will not be a focus in this thesis.

Silica-soda-lime glass and strength values for structural design (annealed glass):

Table 1 – structural properties of glass

Density	2500 kg/m^3
Young's modulus	70 GPa
Passions ratio	0.23
Compressive strength	880-930 MPa
Tensional strength	30-90 MPa
Bending strength	30-100 MPa

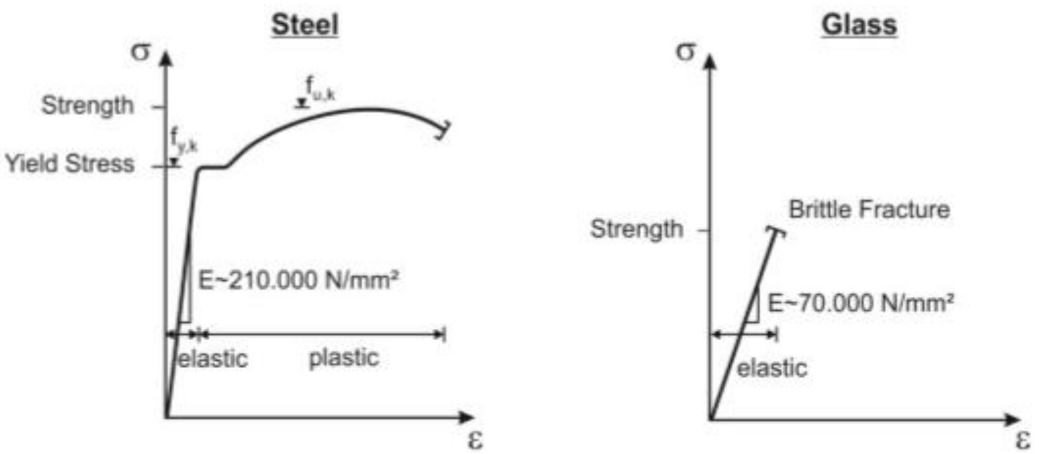


FIGURE 4 - STRAIN - STRESS GRAPHS OF STEEL VS GLASS

Connections

Previous research and theory suggests that the sufficient way to connect the glass stag with the steel flanges is by using adhesives/glued connections [2]. This type of connection is more homogeneous in terms of stress distribution then a bolted connection, which would be the other alternative. The adhesive also isolates the glass web from the steel flange in terms of direct contact, which is a necessity. This is due to the stress concentrations that would occur on the glass web while in direct contact with the flange or a steel connection when the beam is exposed to a given load.

There are many different adhesives on the market. The main types that are considerable for the hybrid model, more specific defined as structural adhesives are the following; Epoxies, Acrylics, Urethanes and Cyanoacrylates.

There a lot of theory implied in the evaluation of what structural adhesive to use in different kinds of structural situations. This table gives an overview of the different types and their relative strengths and weaknesses [3].

Table 2 – Evaluation of different adhesives

Properties	Epoxies	Acrylics	Urethanes	Cyanoacrylates
Overlap shear – Metals	Best	Low to high	Moderate	Low for long-term bonding
Overlap shear – Plastics	Moderate	Best	moderate	High
Peel str.	Low to best	Low to (occasionally high)	good	Low
Impact resistance and thoughness	Poor to best	Poor to good	good	Low
Flexibility	Poor to good	Poor to good	good	Low
Temperature resistance range	best	moderate	moderate	Low
Overlap shear - Thermoset Composites	Best	High	high	Moderate
Solvent resistance	Best	moderate	high	low

The adhesives used in the model is the epoxy resin, which in most cases are viewed as best adhesive in terms of mechanical properties.

Table 3 – Structural properties of epoxy resin

Tensile strength	85MPa
Tensile modulus	10,500 MPa
Elongation at break	0.8%
Flexural Strength	112 MPa
Flexural modulus	10,000 MPa
Compressive strength	190 MPa

Finite element model (FEM) program

A finite element method is solving the behavior of a structure by dividing this structure into several elements. Every element in this structure will need to have certain well-defined properties. This structure is then applied some form of load. To be able to apprehend any form of accurate results from this structure, one needs certain assumptions such as geometry, boundary conditions, material law etc. This will make it possible to convert a mathematical model. The FEM is a numerical procedure that needs to be repeated until a sufficient accuracy is reached.

3 Theory Ansys

BEAM188

BEAM188 is an element that is good for analyzing beam structures that are thin or moderately thick. The element is linear, quadratic or cubic element with 2 nodes and it operates in 3D. It has six or seven DOF at each node. This includes translation and rotation in regards to the x, y and z – axis. The element is well suited for linear, large rotation, or large strain nonlinear applications.

SOLID185:

SOLID185 is used for 3-D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node, with translations in the nodal x, y, and z directions. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. [1]

SOLID185 Structural Solid is suitable for modeling general 3-D solid structures. It allows for prism, tetrahedral, and pyramid degenerations when used in irregular regions. See figure 5 [1].

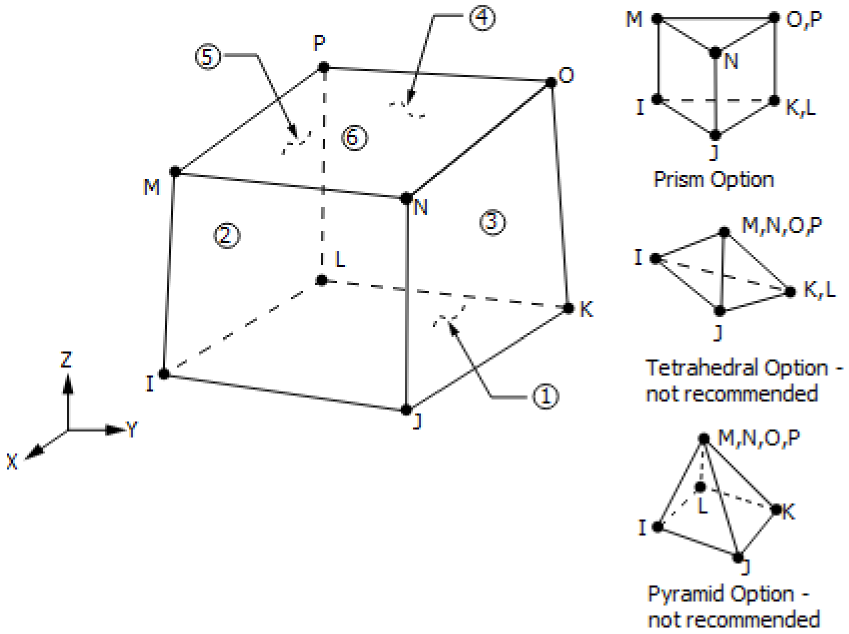


FIGURE 5 - SOLID185 APDL [1]

CONTA174 and TARGE170

CONTA174 is used to represent contact and sliding between 3-D target surfaces and a deformable surface defined by this element. It can be used for both pair-based contact and general contact.

In the case of pair-based contact, the 3-D target element type, TARGE170, defines the target surface [1].

Contact occurs when the element surface penetrates an associated target surface.

Coulomb friction, shear stress friction, user-defined friction, and user-defined contact interaction with are allowed. The element also allows separation of bonded contact to simulate interface failure (mechanical toughness reduction). [1]

The element is defined by eight nodes, see figure 6. If the underlying solid does not have midside nodes, the contact element can degenerate to a six node element [1].

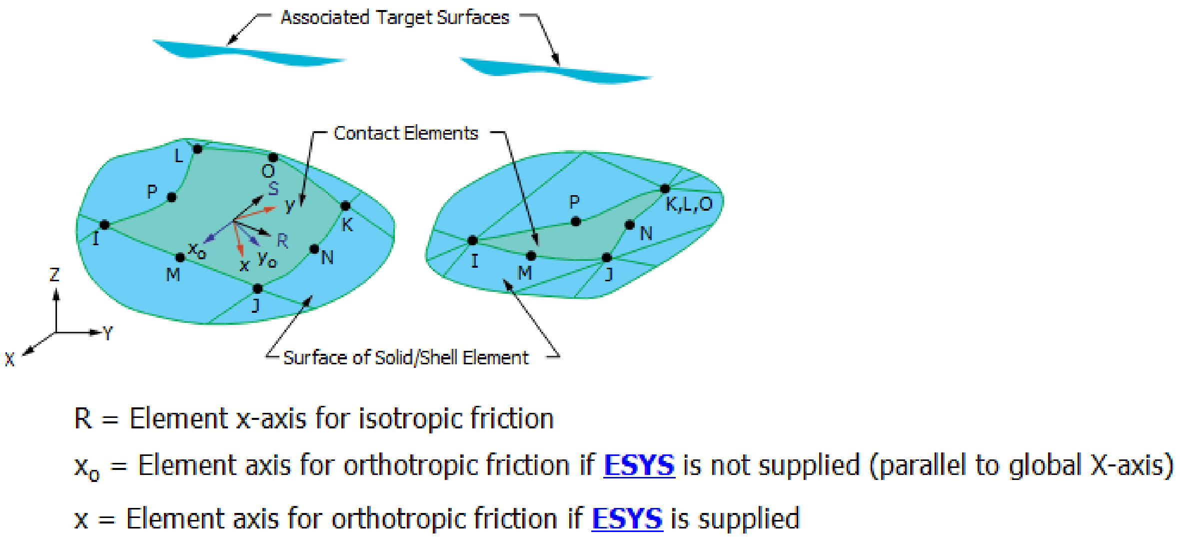


FIGURE 6 - CONTA174 AND TARGE170 [1]

Surface – to – Surface Contact elements

Surface – to – surface contact elements uses a "target surface" and a "contact surface" to form a contact pair [1].

- The target surface is modeled with either TARGE169 or TARGE170 (for 2-D and 3-D, respectively)[1].
- The elements related to the contact surface is CONTA171, CONTA172, CONTA173, and CONTA174.

These surface-to-surface elements are well-suited for applications such as interference fit assembly contact or entry contact, forging, and deep-drawing problems. The surface – to – surface elements can [1]:

- Supports corner – noded and midside – noded elements.
- Provide better contact results needed for typical engineering purposes, such as normal pressure and friction stress contour plots.
- Allow modeling of fluid pressure penetration loads.

Using these elements for a rigid target surface, you can model straight and curved surfaces in 2-D and 3-D, often using simple geometric shapes such as circles, parabolas, spheres, cones, and cylinders. More complex rigid forms or general deformable forms can be modeled using special preprocessing techniques [1].

Surface-to-surface contact elements are not well-suited for point-to-point, point-to-surface, edge-to-surface, or 3-D line-to-line contact applications, such as pipe whip or snap-fit assemblies. The node-to-surface, node-to-node, or line-to-line elements is better to apply in these cases [1].

The surface-to-surface contact elements supports general static and transient analyses, buckling, harmonic, modal or spectrum analyses, or substructure analyses [1].

Normal penalty stiffness

The normal stiffness is the deciding factor regarding the amount of penetration that will occur the pair – bases contact and target surface, while the tangential stiffness decides the amount of slip between elements that will occur [1].

The normal range for the normal stiffness factor is 0.1 – 10, while the default value is 1. Increased value reduces the amount of penetration/slip, but it can cause problems for the global stiffness matrix and make the convergence difficult.

Penetration tolerance is based on the depth of the underlying solid, shell or beam element and has a value under 1.0. the default value for this is 0.1.

Contact Algorithms

For the surface-to-surface contact elements, there are the different options for the contact algorithms [1].

- Penalty method
- Augmented Lagrangian method
- Lagrange multiplier on contact normal and penalty to tangent
- Internal multipoint constraint.

The penalty method uses a contact “spring” to establish a produce a relation between contact and target surface. The spring stiffness is called the contact stiffness. [1]

The augmented Lagrangian method is an extended version of the penalty method and is based on an iterative process. The contact tractions are augmented during the equilibrium iterations so that the final penetration is smaller than the allowable tolerance. Compared to the penalty method, the augmented Lagrangian method leads to better conditioning and is less sensitive to the magnitude of the contact stiffness [1].

The pure Lagrange multiplier method enforced zero penetration and zero slip and does not require contact stiffness. This algorithm often increases the computational cost compared to the augmented Lagrangian method. [1]

An alternative algorithm is the Lagrange multiplier method applied on the contact normal and the penalty method (tangential contact stiffness) on the frictional plane. The method establishes zero penetration. It requires chattering control parameters and also maximum allowable elastic slip parameter [1].

The last algorithm is the internal multipoint constraint (MPC) algorithm, is used in conjunction with bonded contact and no separation contact to model contact assemblies and kinematic constraints [1].

Contact detection

The most common methods are the nodal detection and the Gauss integration points. The difference is that nodal detection uses each node as integration points while the Gauss integration uses integration points between the nodes [1].

Behavior of Contact surface

The relevant options in regards to surface – to –surface contact [1]:

- Standard
- Rough
- No separation
- Bonded
- No separation always
- Bonded always
- Bonded (initially)

In the model presented in this thesis initially bonded was chosen. The contact detection points that are initially closed will remain closed to the target surface. The contact detection that are initially open will remain open.

4 Execution

Former research [2, 5, 9] has been made on adhesively bonded steel and glass beams and the most common intersections that has been evaluated in regards to this type of hybrid composite beam is given in the figure 7. All variants include adhesive as the connection (hatched lines), Steel flanges (gray lines) and glass web (blue lines). Figure 7“a “describes the basic concept, which is also the intersection the analytical model is based on. Figure b and c is building on this basic concept and tries to give solutions to how one can best support the adhesively bonded connection and reducing the chance of displacement relative to the steel flanges. (These models only illustrate the concept and does not consider dimensions.)

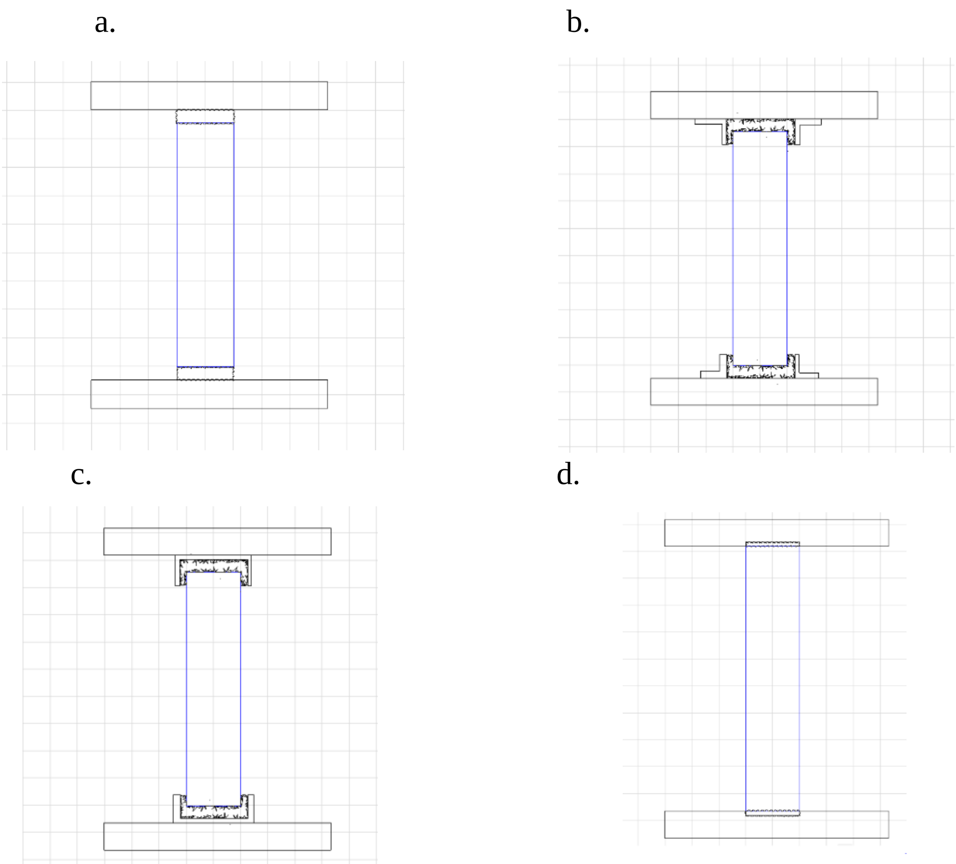


FIGURE 7 - CONCEPTS FOR HYBRID GLASS-STEEL BEAM

The concept presented in figure b will be the focus in this thesis. Both concepts in b and c give a solution to how one can hold the epoxy in place. The increased area of contact where the epoxy is working increases, reducing the chance of contact failure.

Furthermore, I have decided to use a common steel beam I – section IPE330, as a frame for the dimensions, although, given the vast difference in tensional strength capacity, the web of glass will be two times the thickness of the original IPE330. The beam will have a length set at 4 meters.

Table 4 – Chosen geometry for hybrid beam

b	160 mm
e	11,5 mm
h	330 mm
T(g)	2x b IPE330 = 15 mm
Angle bracket	3mm x 10mm L bracket with symmetry around the corners
Epoxy	2mm layered epoxy in the gap between web and brackets and flanges.

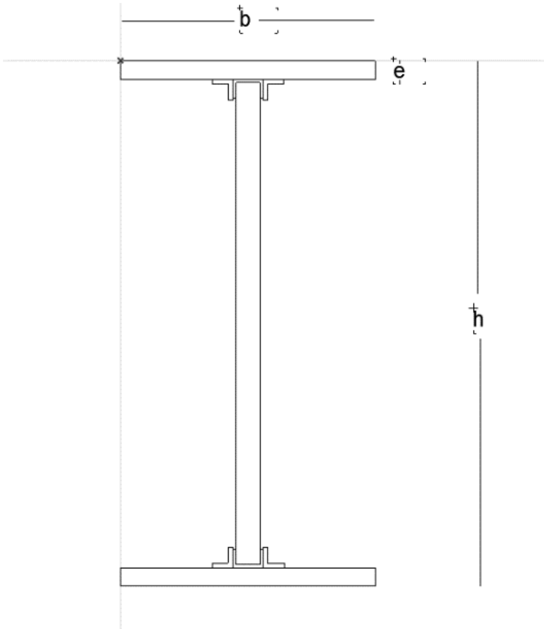


FIGURE 8 - GEOMETRY HYBRID GLASS-STEEL BEAM

Ideally, one would like to have a perfect connection where the hybrid beam would work as one element and that the stress distribution would look like the distribution you would see in a common steel beam. However, some of the shear force will in reality transfer in to displacement along the axis of the beams length as illustrated in the figure 9(because of imperfect connection). Δ_1 and Δ_2 are exaggerated. It shows what will happen (theoretically) if the adhesive is extremely weak or if there were no adhesive/connection between the elements. This displacement should be close to zero in all load cases.

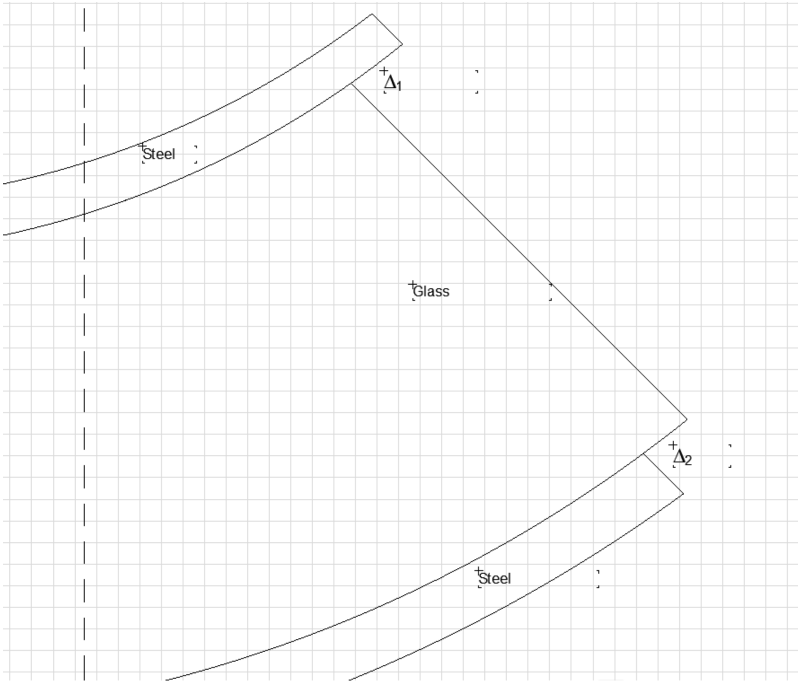


FIGURE 9 - SLIP FLANGE/WEB ILLUSTRATION

When making the model in a finite element program there will be solutions concerning the capacity of the epoxy and the occurring displacement shown in figure 9. However, in conduction of hand calculations I will assume that the connection is perfect, difference in displacement shown in figure 9 is equal to zero, and all stresses are distributing according to the components elasticity and Area. Given that, glass is an elastic material and does not have any plastic phase the hand calculations for this model will be elastically.

The beam will have a length set at 4 meters and be loaded with q (kN/m). Excluding Angle brackets. Assuming perfect connection with the glass web running all the way up to the flange. The purpose of this is to define a simplified understanding of the model and get an estimate of what this section could hold with perfect contact between the steel and glass.

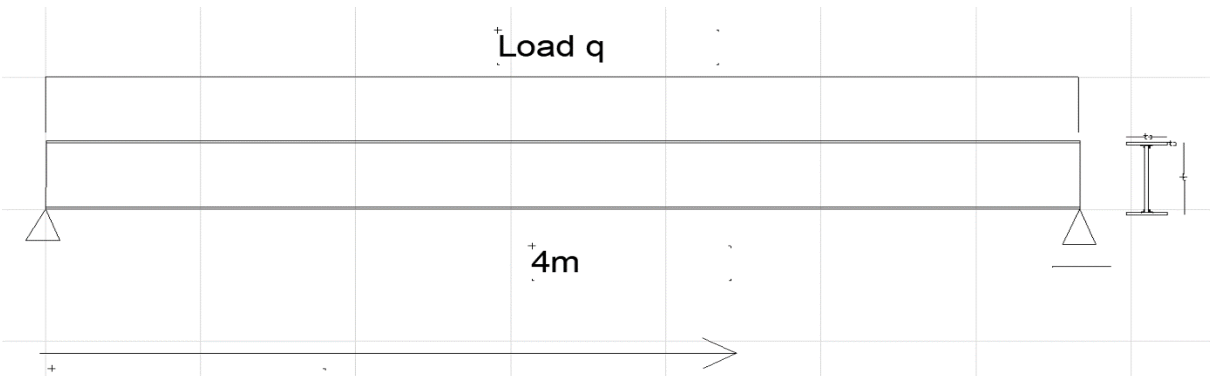
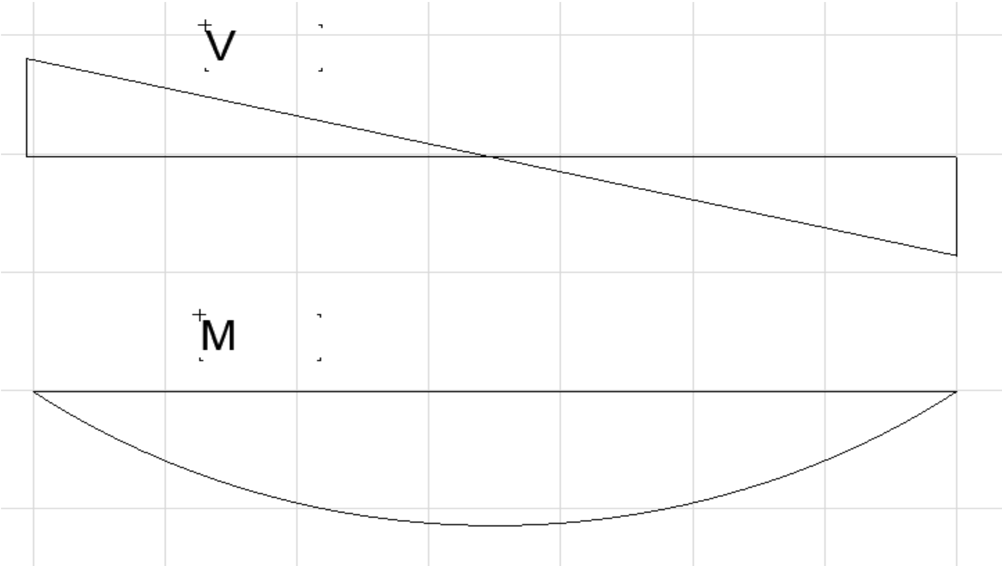


FIGURE 10 - LOAD CASE FOR THE THEORETICAL MODEL



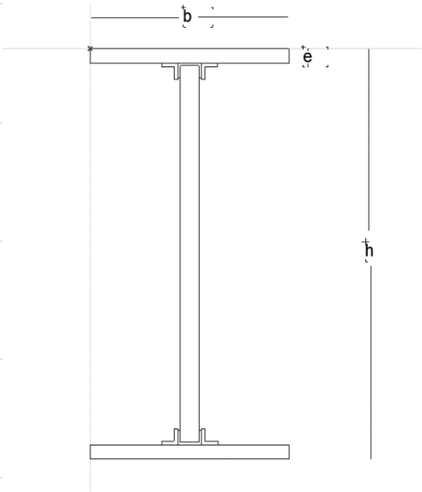


FIGURE 11- OCCURRING MOMENT AND SHEAR ON BEAM

Table 5 – Values used in calculations

B	160 mm
E	11,5 mm
H	330 mm
T_g	15 mm
E_g	70 x 10 ^{3} MPa
E_s	210 x 10 ^{3} MPa
$A_{flange, lower} = A_{flange\ upper}$	1840 mm^2
A_{web}	4605 mm^2

Furthermore, the assumption of a perfect connection implies a shear- and normal stress distribution given in Figure 12:

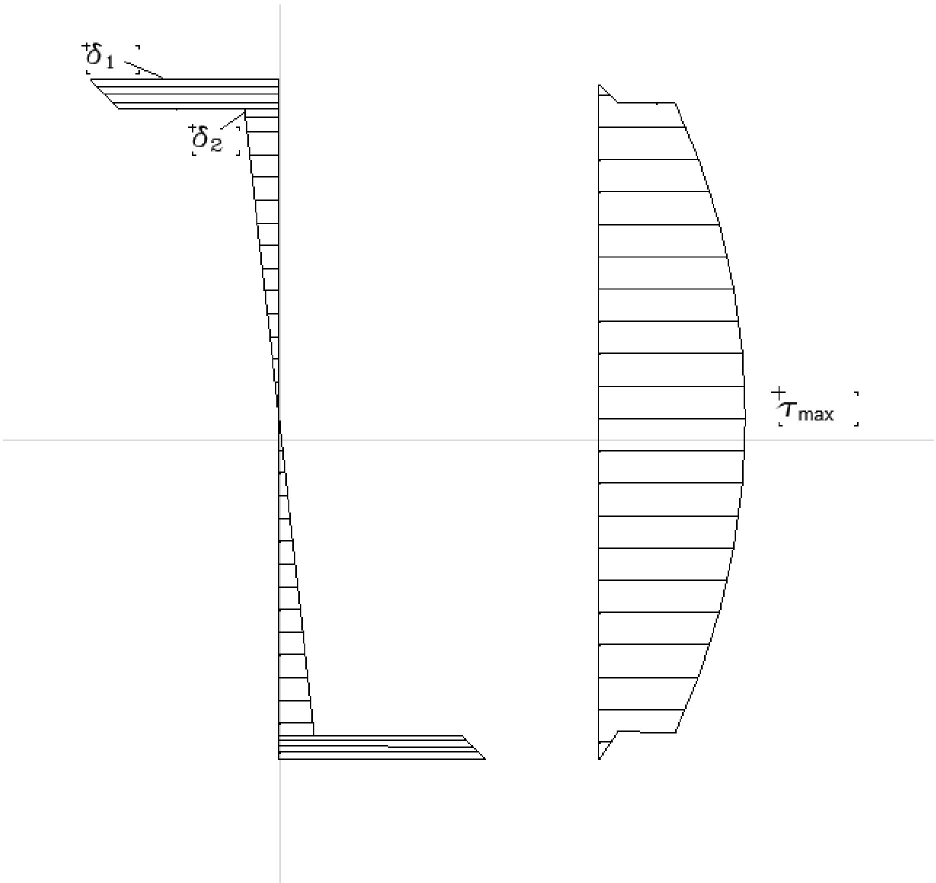


FIGURE 12 - SHEAR AND BENDING-STRESS DISTRIBUTION (PERFECT CONNECTION)

Calculations

The calculations are conventional, but we need to apply the “Equivalent Area” method. This method transforms one material’s cross sectional area to facilitate the other materials that is present [6]. Similar approaches are used in former studies with the same type of steel – glass configuration [5].

The relation between the different elasticities makes the convergence:

$$n = \frac{E_s}{E_g} = \frac{2.1}{0.7} = 3$$

The beam section is symmetric; the centroid of the beam is equal to;

$$y, centroid = \frac{\sum yi * Ai}{\sum Ai} = \frac{330}{2} = 165mm$$

Defining the section moment of Inertia:

$$I_{f,bottom} = I_{f,upper} = \frac{1}{12} e h^3 = \frac{1}{12} * 160 * 11{,}5^3 = 20278{,}33\ mm^4$$

$$I_w = \frac{1}{12} T_g h^3 = \frac{1}{12} * 15 * (330 - 2 * 11{,}5)^3 = 36168053{,}75\ mm^4$$

$$I_{f,tot,equivalent} = I_{f,bottom,equivalent} + I_{f,upper,equivalent} = 2I_{f,upper,equivalent}$$
$$= 2 * \left(I_{f,upper} + A_{f,upper} * z_{f,upper}^2\right)$$

$$= 2 * \left(13750 + 1840 * \left(165 - \frac{11{,}5}{2}\right)^2\right) = 93367427\ mm^4$$

$$I_{equivalent} = I_{f,tot,equivalent} + \frac{I_w}{n} = 93367427 + \frac{36168053{,}75}{3} = 105423445\ mm^4$$

Section of modulus;

$$W_1 = \frac{I_{equivalent}}{y, centriod} = \frac{105423445}{165} = 638930\ mm^3$$

$$W_2 = \frac{I_{equivalent}}{y, centroid - e} * n = \frac{105423445}{165 - 11,5} * 3 = 2060393\ mm^3$$

With these sectional properties, we can calculate the capacity for the model and determine an estimated max load q over the length of 4 meters. The dimensional bending stress for this model when assuming perfect contact between the elements, are the Normal tensional stress occurring in the lower end of the glass web. The glass has a tensional capacity of 30 MPa the maximum moment that can occur is the following:

$$\sigma_{limit,glass} * W_2 = M$$

$$M = 30 * 2060393 = 61811792\ Nmm \approx 61,8kNm$$

Given beam length of 4 meters the dimensional q regarding Normal-bending stress for the beam is:

$$q = \frac{8M}{l^2} = 8 * \frac{58}{16} = 30,9\ kN/m$$

Relevant Shear stress occurring in the support is:

$\tau_{dim,glass} = 30\ MPa$

Solving for V in regards to shear capacity. This will be where the maximum shear occurs in the center of gravity of the beam section.

$$V = \tau_{dim,glass} \frac{I_{equivalent} * b}{S_y}$$

$$S_y = \frac{A_w}{2} * \frac{h-2e}{4} + A_f * \frac{h-e}{2} = \frac{4605}{2} * \frac{330-2*11,5}{4} + 1840 * \frac{330-11,5}{2} = 469736,9mm^3$$

$$V = 30 * \frac{105423445 * 15}{469736,9} = 101kN$$

The related q is:

$$q = \frac{2V}{l} = 2 * \frac{33,66}{4} = 50,5kN/m$$

Implying that the bending stress (tension) occurring in the lower web will be the dominating factor for the glass web.

Deflection with optimal load q = 30,9 kN/m:

$$\delta = \frac{5}{384} * \frac{ql^4}{E_{steel} * I_{equivilent}} = \frac{5}{384} * \frac{30,9 * 4000^4}{2.1 * 10^6 * 105423445} = 4,6\ mm$$

The reason E_{steel} in the calculation of displacement is due to conversion. The beam is consisting of only steel (mathematically). The effective area of the web have been reduced to the point where $\sigma_{Steel} * A_{s(web)} = \sigma_{glass} * A_{glass(web)}$. For the moment of inertia to be the equivalent, the reduction in area has to be lateral and not vertical. Keep in mind that this conversion is also only valid for this calculation when regarding I_y. Aka about the y-axis.

FE - Model 1

Critical modification: Reduced the thickness of the web to the extent where the thickness of the web has a thickness that gives the same Moment of inertia, regarding the relative factor between the elasticities between glass and steel. The moment of inertia remains constant and the stress distribution stays the same. However, the bending stress occurring in the critical point of the web will be 3 times the actual stress occurring in web. This is due to the reduced thickness of the web.

This model will give some verification to the calculations and make it reasonable for further investigation of possibilities for optimization of the intersection in regards to shear and bending stress capacities.

The thickness of the web will therefore in the model be 15/3 = 5mm.

The simplified model a normal IPE 330 with intersection except for the 2.5mm diff in the thickness of the web. The intersection is given in the figure 13 with a span of 4000 mm.

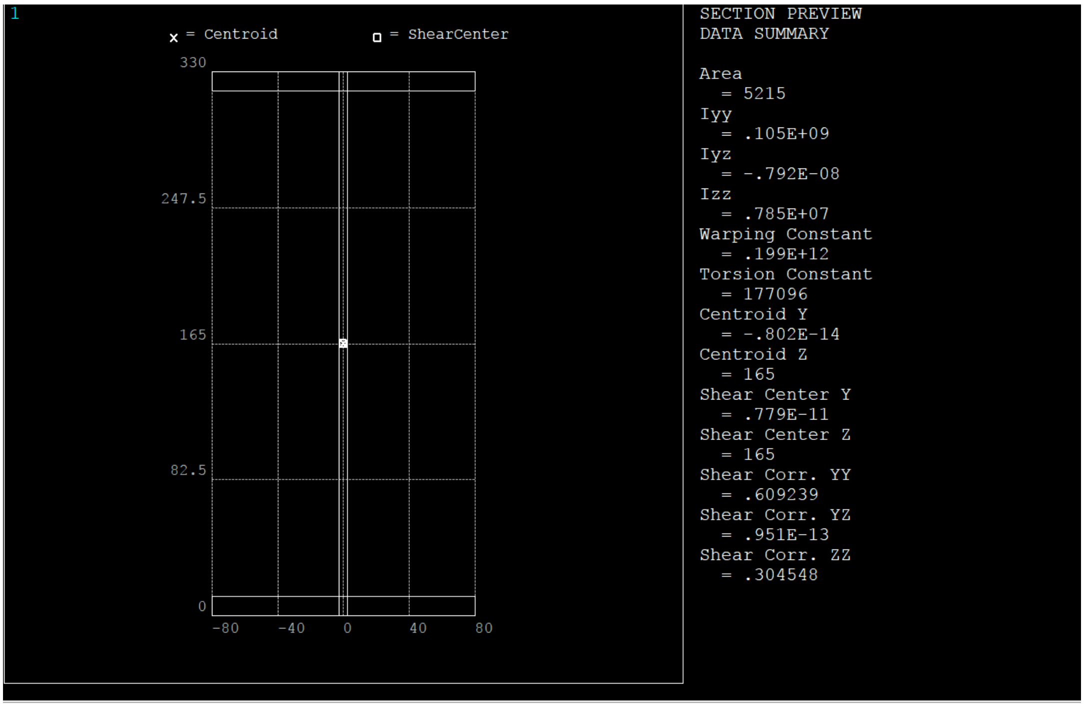


FIGURE 13 - INTERSECTION OF FE-MODEL 1

As this was the first approach and a very simple simulation that does not include different materials or contact – pairs between the flange and web I will only give a very short summary of the modelling phase.

i) Defined element: BEAM188 (requires no real constant)
ii) Defining materials (steel) with E – modulus = 2.1e5 and PRXY = 0.3
iii) Making the beam section by using sections -> common sections Figure 13.
iv) Defined the constraints in Ansys to simulate a simply supported beam(As given in the calculations)
v) Defined Loads equal to the calculated capacity of the beam in regards to the tensional stress capacity of the glass web. (See calculations)

The occurring deflection was 5.13 mm at the critical point as shown in figure 14.

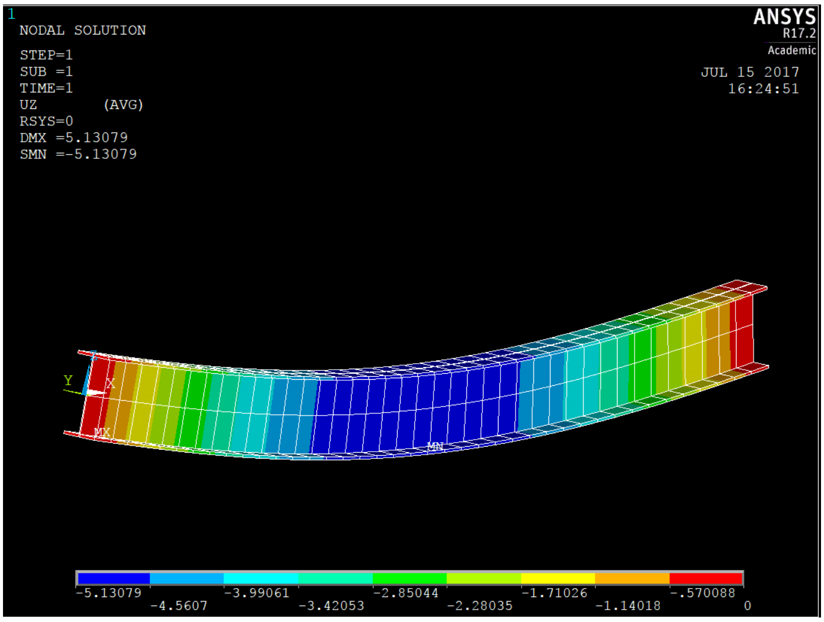


FIGURE 14-DEFLECTION FE-MODEL 1

One thing to note here is that the deflection deviates from the calculations with roughly (5.1/4.6 = 0.98) 10%, The constraints in all models in this thesis is placed on the lower lines of the lower flange. The loads in this model is defined as areal pressure (N/mm) on the upper flange equivalent to the dimensional line load 30.9N/mm that was calculated. 30.9/160 N/mm^2.

The occurring bending stress in the model 1 is displayed in figure 15.

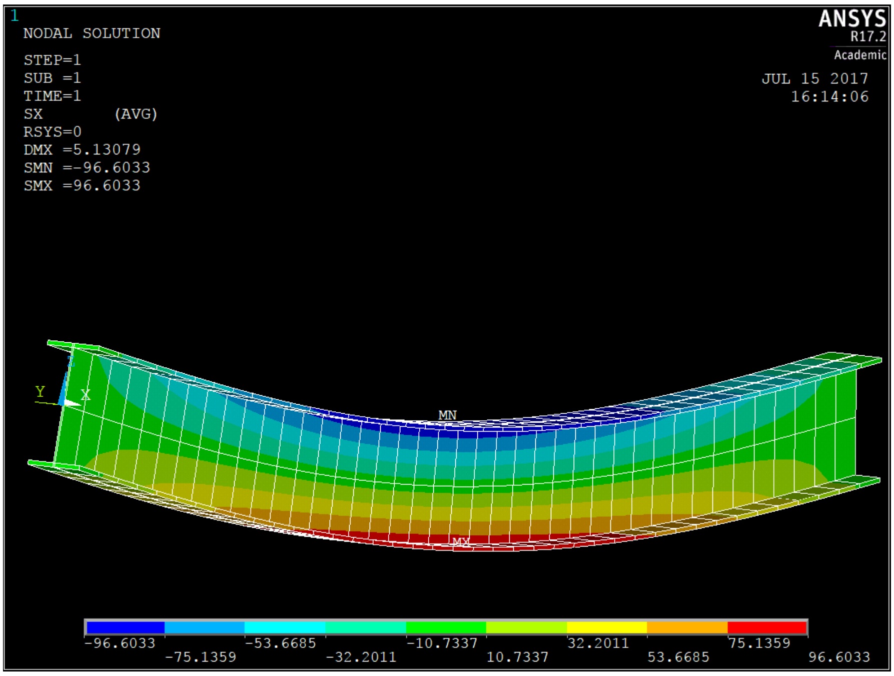


FIGURE 15 - BENDING STRESS FE - MODEL 1

The bending stress occurring in this model seems to fit the calculations, as the lower web is enduring tension around 90 MPa three times the calculated value. This was expected, as the web in this model is 3 times thinner than the glass web chosen for the hybrid beam.

FE – Model 2

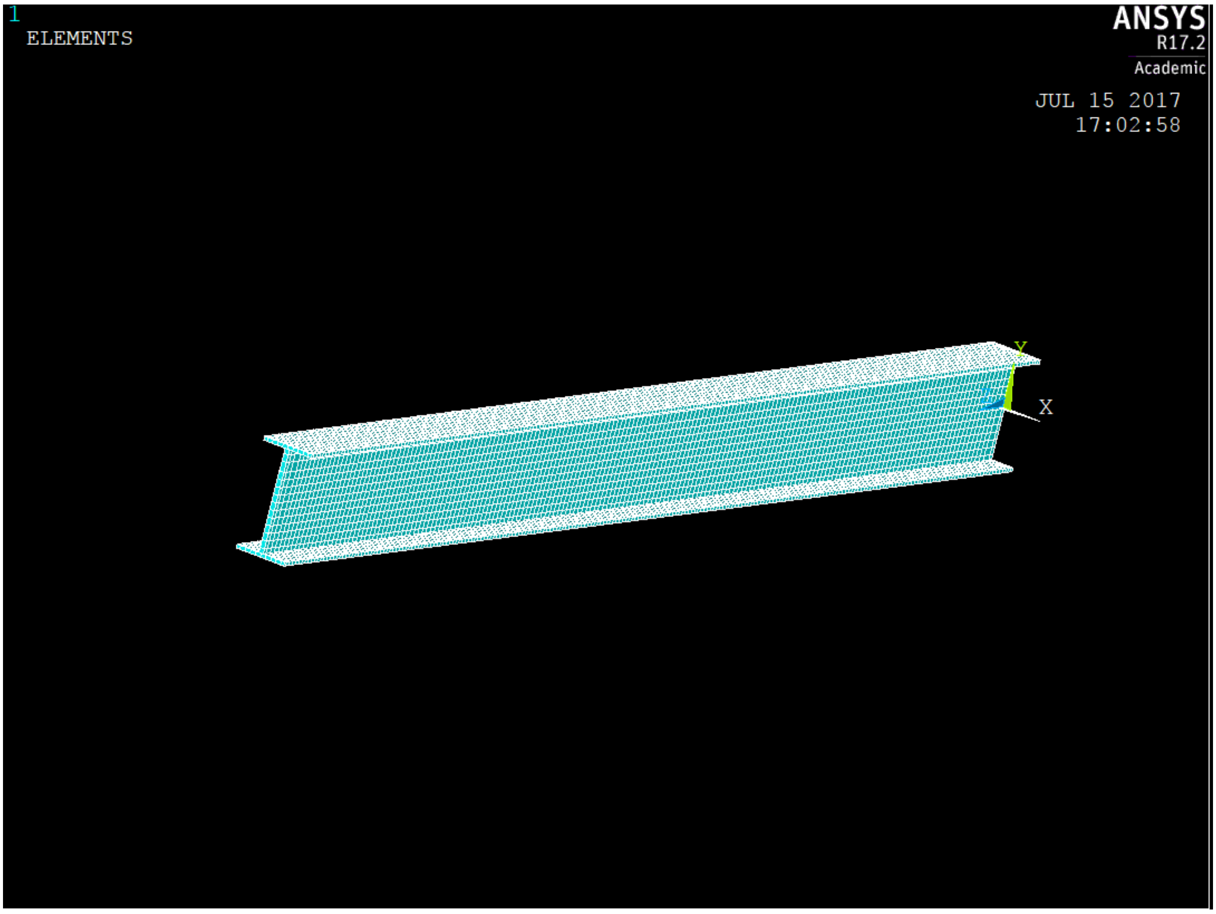


FIGURE 16 – FE-MODEL 2

Figure 16 displays FEM 2 containing three types of materials: Steel, glass and epoxy. The following steps will give a somewhat accurate description on how the model was constructed and some reasoning to the decisions made under the process.

i) Creating the cross-section of the beam:

1) Drew the relevant cross - section of the beam containing of three arenas; upper flange, lower flange and the web with same dimensions as the cross-section given in table 1.3. See figure 1.10.
2) All three areas was extruded to a length of 4000mm in the normal direction giving the beam the main volume displayed in figure 1.9

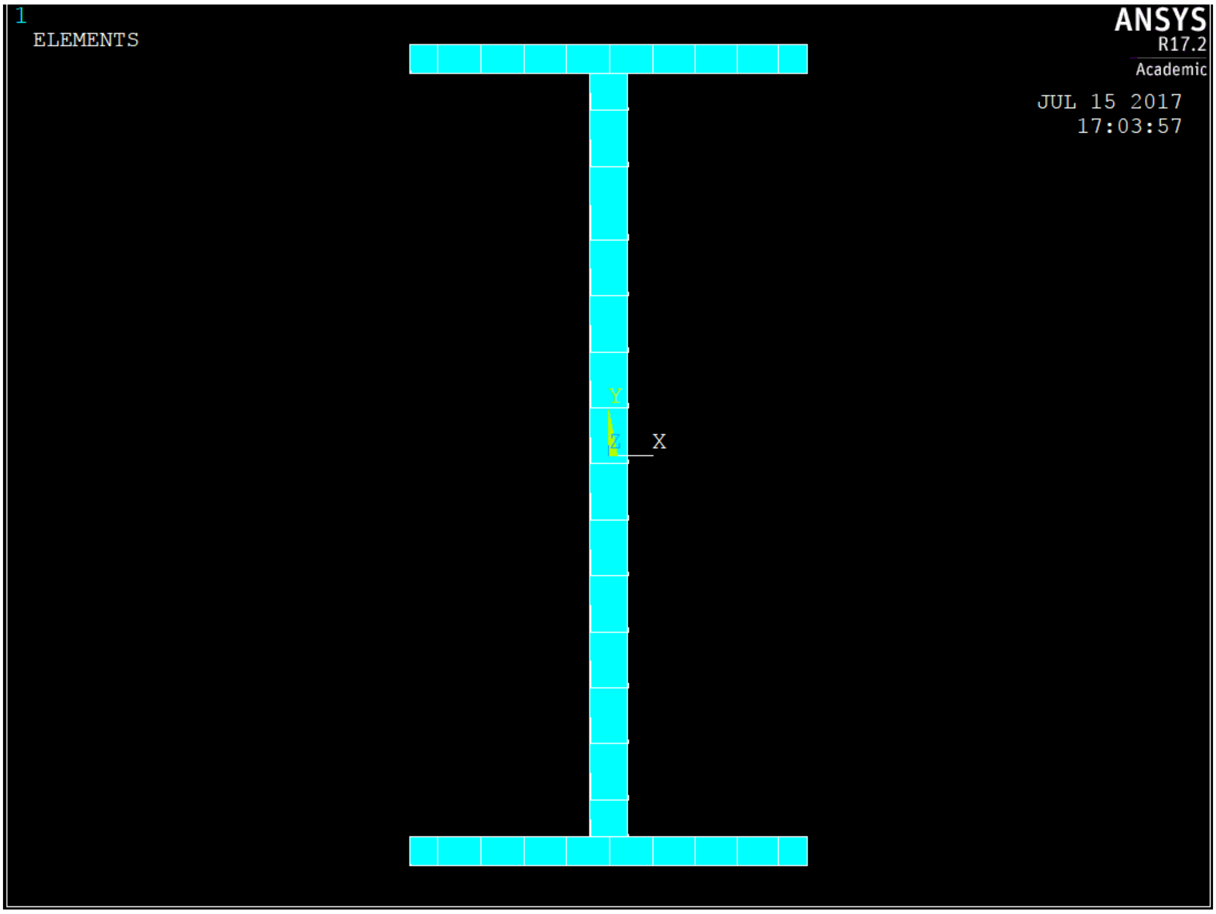


FIGURE 17 – FE-MODEL 2 INTERSECTION

ii) The element chosen for both the glass and the steel is SOLID185 as it gives good accuracy for elastic materials. There are also the target and contact elements that were implemented in the contact pair.

iii) Both steel and the glass is defined as isotropic elastic material with the properties shown in figure 1.11.

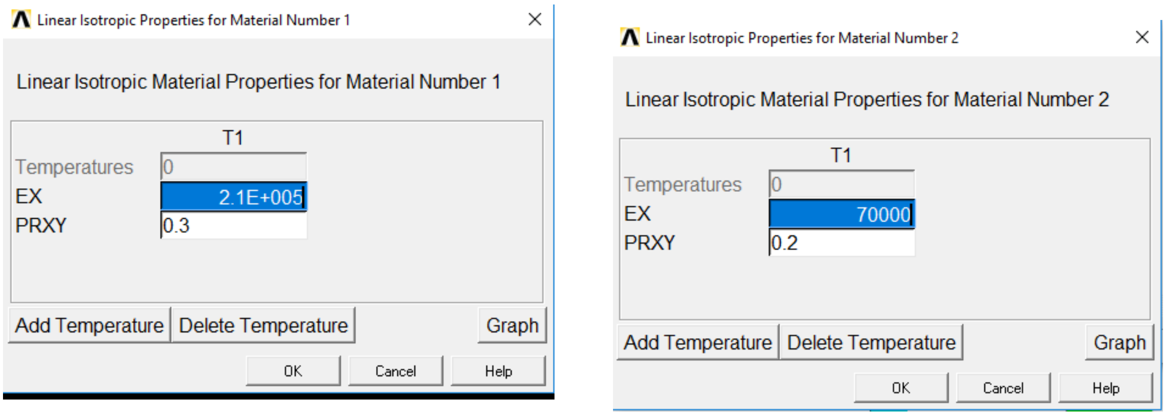


FIGURE 18 - PROPERTIES OF GLASS AND STEEL FEM 2

iv) The contact pairs were defined on the interfaces between the flanges and the web shown in figure 19 with spesifications described in figure 20

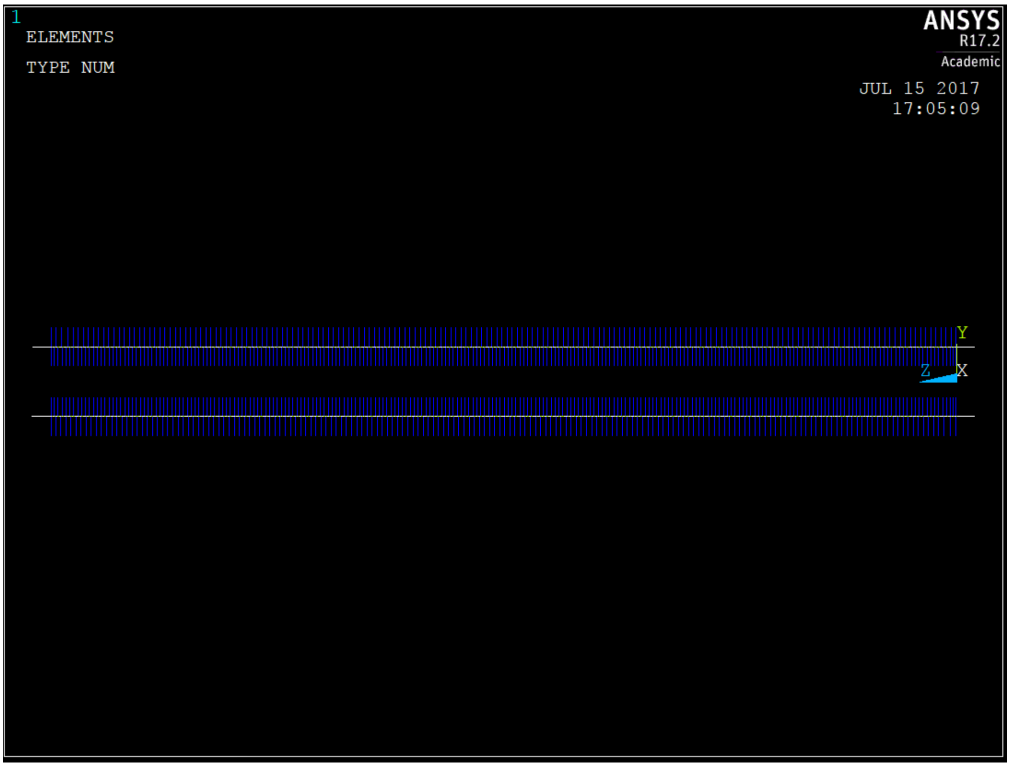


FIGURE 19 - ILLUSTRATION OF CONTACT PAIR FE-MODEL 2

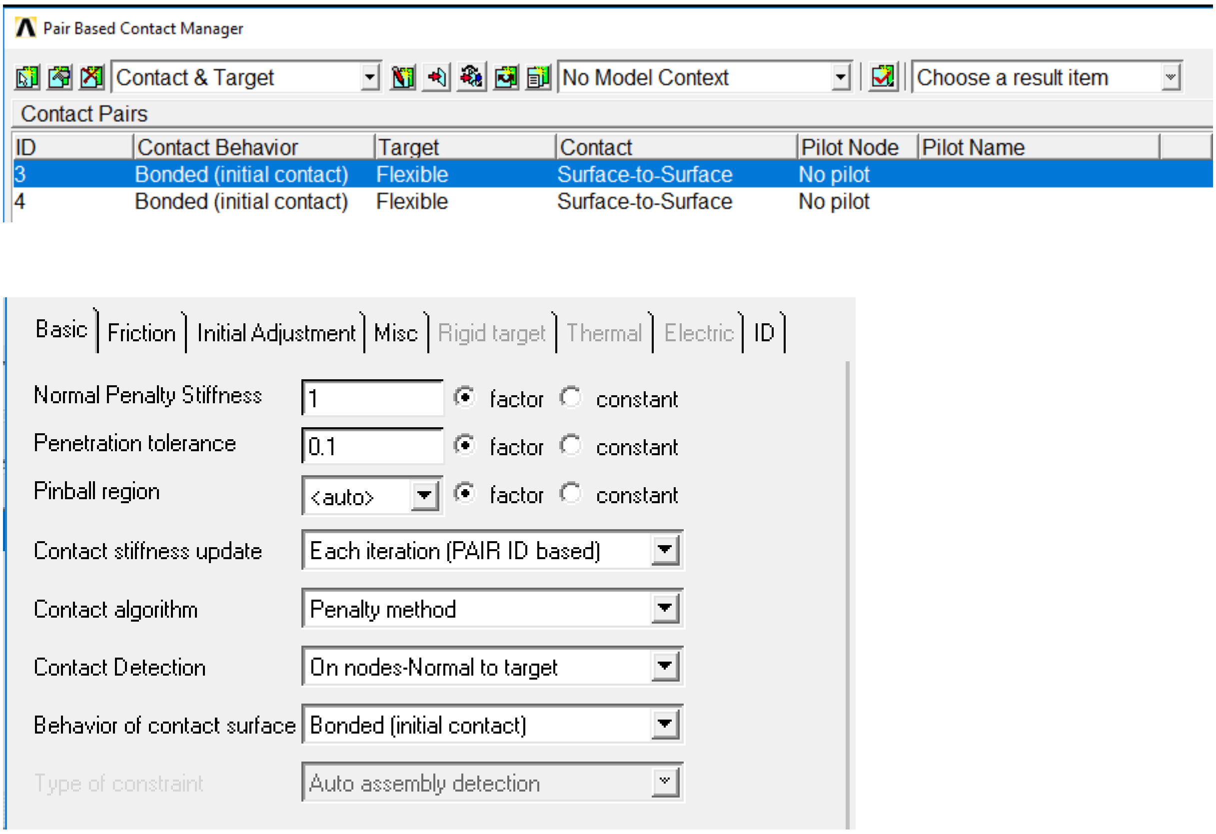


FIGURE 20 - SPECIFICATIONS FOR THE CONTACT PAIR FE-MODEL 2

- Normal Penalty stiffness is set to default equal to 1. Increasing this value reduces the allowable penetration/slip but it will also make convergence of the model more difficult.
- Penetration tolerance is set to default equal to 0.1. In this case its related to the underlying Solid.
- Contact algorithm chosen is the penalty method. It is a simplified version of the Augmented Lagrangian method, which is the default algorithm for this type of contact element (contact algorithms, chapter 3).
- The default values for the behavior is bonded allways. As I wanted to have slip (as in deltas parallel to the beam length, between the elements). I chose the behavior to bonded (initially). This also ensured that the elements would be in contact during the solution.

v) Constraints and loads (figure 1.14):

- The DOF constraints on this model is based on the same scenario as the previous model and hand calculations; simply supported beam. Longitudinal (z) and vertical (y) has a displacement set to zero in the line of the lower flange on the left hand side, while on the right hand side the displacement of the related line is set to zero in only the vertical direction(y).
- The loads are applied along 236 nodes that gives the equivalent distribution of loads as the calculated capacity of the beam with ideal connection. The nodes that are applied this force is the center nodes on the upper area of the beam as displayed in

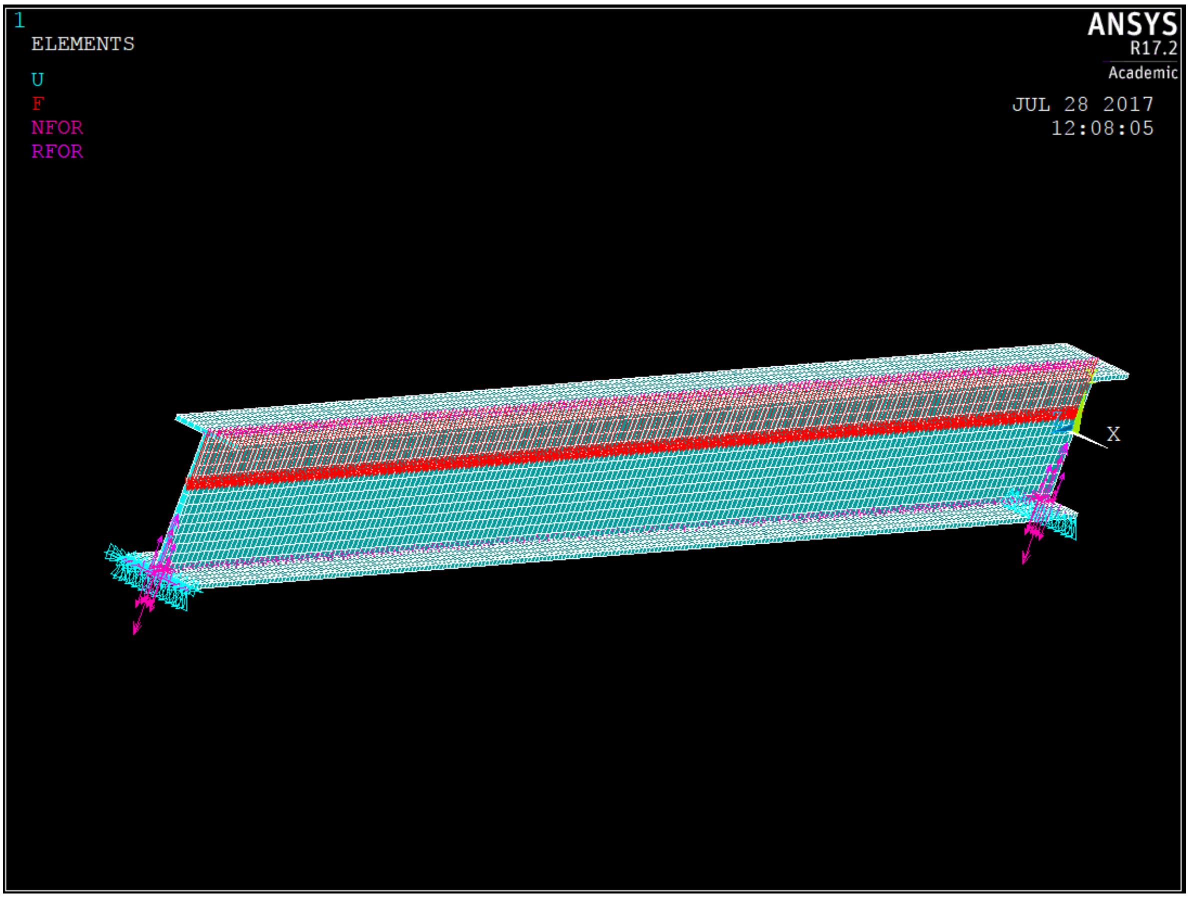


FIGURE 21 - CONSTRAINTS AND LOADS FOR FE-MODEL 2

5 Results

Listing results from FEM 2 models where the deltas in Max shear force, Y – displacement (vertical displacement), bending stress and relative z displacement between the flange and the web will be in focus.

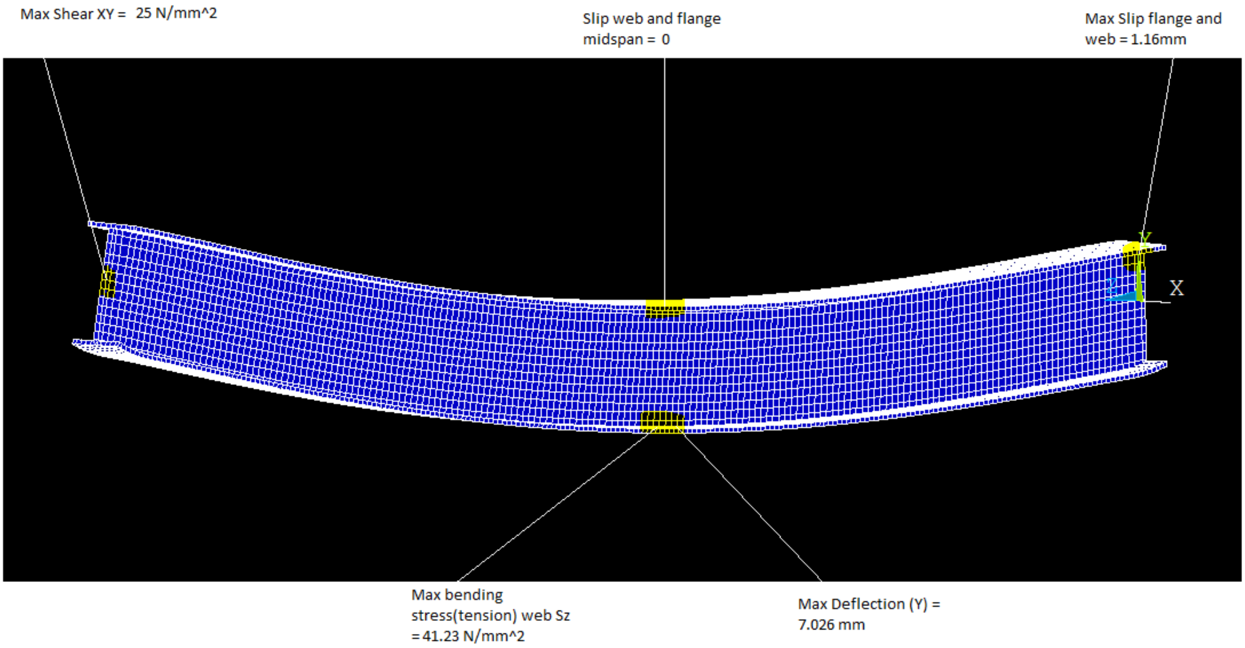


FIGURE 22 – FE-MODEL 2 SUMMARY RELEVANT STRESSES AND DEFLECTIONS

Given values was found by selecting the critical nodes on the beam and looking at the occurring nodal solution (under list results).

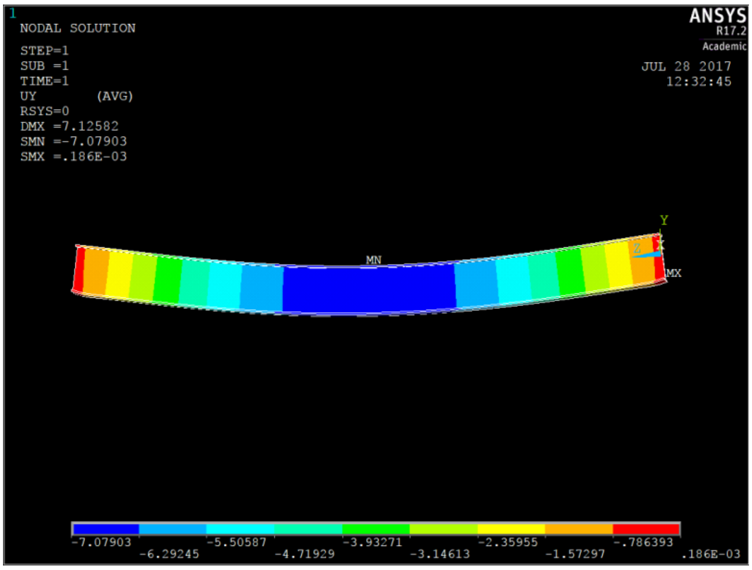


FIGURE 23 - Y DEFLECTION OF FE-MODEL 2

Bending-stress distribution: The figure shows some a few Local stresses that is not considered. The max bending stress in focus is found in nodal solution at the calculated max (glass) with value of 41.23 N/mm^2.

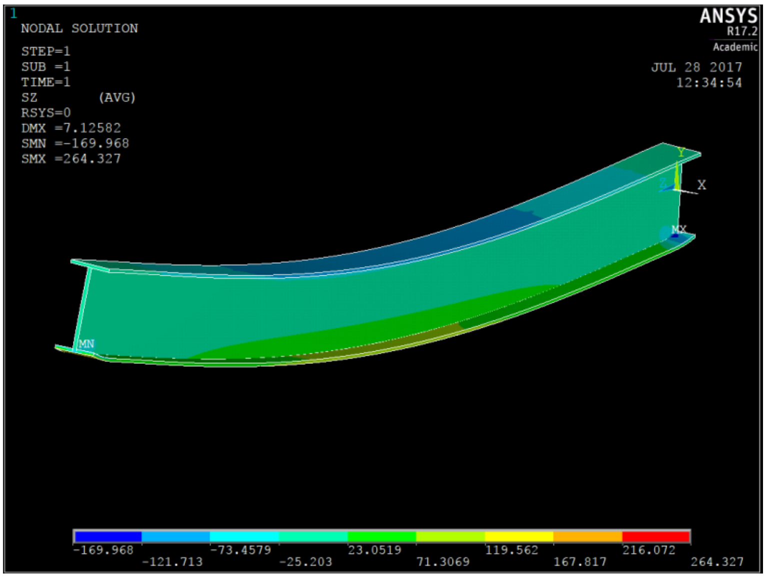


FIGURE 24 - BENDING STRESS OF FE-MODEL 2

Nodal solutions for model 2 Ansys

Slip D = D Z deflection between the nodes

= 1.2564 – 0.088064 = 1.16834 mm

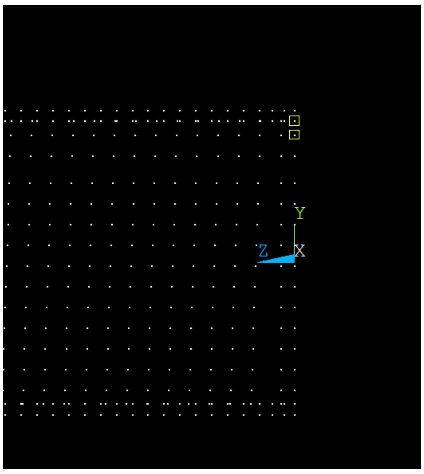


FIGURE 25 - SLIP BETWEEN WEB AND FLANGE AT END OF BEAM)

Bending-stress Z (max stress occurring on glass web). This is at mid span of the beam on the lower point of the glass web.

= 41.23 N/mm^2

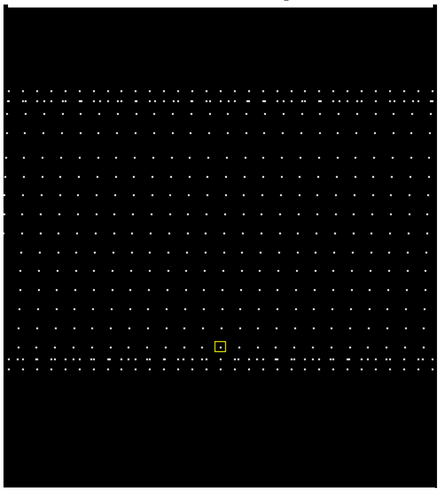


FIGURE 26 - OCCURRING BENDING STRESS AT CRITICAL POINT OF GLASS WEB

Shear XY(max)

= 25 N/mm^2

(end of the beam at mid web)

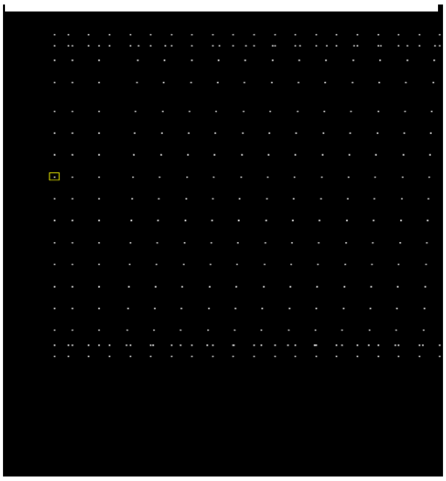


FIGURE 27 - MAXIMUM SHEAR ON GLASS WEB

Z Delta mid beam flange and upper web (Node Flange 5239= - 0.67712, Node web 10387: -0.67304) this was expected. Indicating a zero slip between flange and web at mid beam.

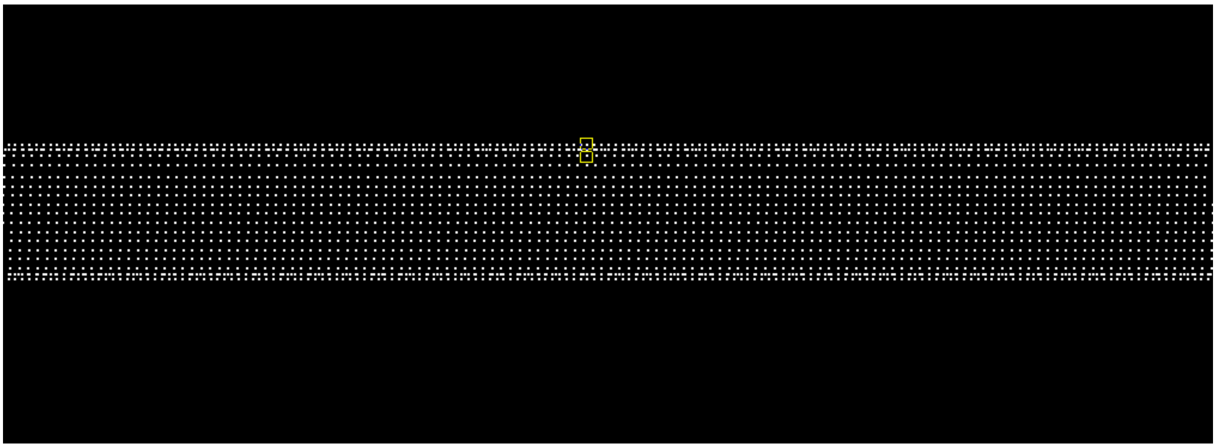


FIGURE 28 - SLIP BETWEEN FLANGE AND WEB MID SPAN

Table 6 - Overall summary of the crucial occurring stresses and the relevant deflections.

Model	Shear XY	Bending-stress Z(max stress occurring on glass web)	Slip D	Vertical deflection
Theoretical model	18.36 N/mm^2	30 N/mm^2	0	4.6 mm
Model 1 Ansys	20 N/mm^2	32.0 N/mm^2	0	5.1 mm
Model 2 Ansys	25 N/mm^2	41.23 N/mm^2	1.16 mm	7.026 mm

6 Discussion

Shear

As expected the shear stress occurring in the glass did not affect the glass capacity. The final model gives results that are higher but still not over the capacity of glass in regards to shear strength. The main concern is the shear stress occurring on the epoxy resin. Theoretically, the shear strength of the epoxy is higher than the value occurring in the nodes near the contact element.

Bending stress

As mentioned previously, the models is based on the allowable stress of the constructed model in regards to bending stress (tensional) if there were prefect contact between the web and flange. As expected FE - model 2 did extend this limit when imperfect contact was implemented, changing the stress distribution in the cross section. Structural glass has a higher theoretical tensional capacity and the allowable tension used in this thesis is based on the lower boundaries of its tensional strength potential. There are tests confirming that glass can have a practical tensional strength of well over double of what this thesis is implying, so the capacity of the beam will depend on the quality of the glass.

Slip

As discussed in sub chapter about occurring slip (if imperfect contact), slip is a key factor when working with adhesively bonded contact. If the limit of elongation is subdued, the contact will fail and the beam could collapse. The maximum slip found in FEM 2 with contact elements was around 1.16 mm. At mid span the slip was 0 implying an elongation of the adhesive layer of 1.16 mm. Epoxy has an elongation at break equal to 0.8%. Looking at the adhesive layer as one continuous element, the percentile expansion in tangential beam direction is 1.16/2000 = 0.00058 which is far less than the limit regarding this matter. In addition to that the L – brackets that was chosen for this model has not been implemented in the model. These brackets would increase the overall contact area increasing the total frictional force of the contact between the elements. It is important to point out that the conduction and results regarding the adhesive layer in the FEM-model is not been verified by calculations or a real laboratory test. However, it suggests a trend for how the beam would act when the flange and web has an imperfect homogenous contact with structural properties of epoxy resin.

Vertical Deflection

The deflections shown in table 6 indicate an increased deflection at mid span of 37%, which is an increase that is higher than the other increases when including imperfect contact. However, the deflection is low considering the ration between the length of the beam and the deflection. 7 /4000 is far less than the requirements in regards to serviceability when considering steel and timber beams.

7 Optimization

The two dominating factors that my optimization is based on is the Architectural optimization and the Structural optimization.

Architectural Optimization:

Glass and steel are two elements that complement each other, and a lot of steel could in some cases be esthetically sufficient, but for this discussion, I will assume that an increase in glass and reduction in steel, increasing the overall transparency is the goal.

- Glass has strong compressive properties, implying that one way to optimize the beam in regards to increasing the glass to steel ratio, would be to replace the upper steel flange with a glass flange. However, this is reducing the absolute moment of inertia, which in turn will increase the total deflection of the beam. This can be fixed by increasing the total area of the glass flange to the point where the relative moment of inertia would be sufficient. An Illustration for this type of hybrid is displayed in figure 29.

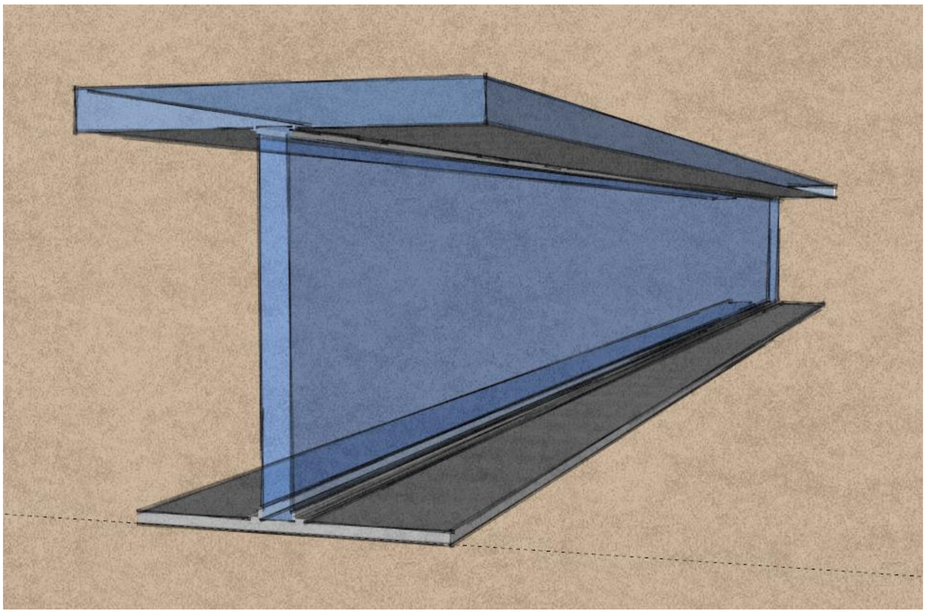


FIGURE 29 - HYBRID BEAM WITH UPPER FLANGE OF GLASS

- Increase in total cost of the beam and the total volume it would occupy, but it would give steel the sole purpose of taking the tensional stresses and increase the total transparency of the beam.
- The beam section would become asymmetric. This would change center of mass and the stress – distribution would alter.
- The contact between web and upper flange would need to change.

Structural Optimization

When discussing this one has to keep in mind that the minimum glass allowed for this hybrid beam is what is already there. These are the options I would recommend to look at:

- Increasing the webs thickness would decrease the occurring tensional bending stress in the web which seems to be the dimensional capacity of the beam at its current state. As the width of the beam is increased, reduced shear stress will occur. Furthermore it will increase the effective area of contact between the flanges and web increasing the total Frictional force. This would imply an overall improvement of the limit state values for the beam. The consequence of thickening the web is a reduction in transparency. One idea could be to study the relation between the thickness of the glass and the transparency. This is however dependent on the beams location and its needs for its specific case.
- Increase the thickness of the steel flanges would increase the moment of inertia and that would reduce the total deflection and occurring stresses.

8 Overall improvements and Future work

Ansys model 2

- Glass is a far more complicated material then what is indicated in the modelling in this thesis. Local stresses occurring on the glass could lead to a collapse of the beam.
- Material modelling must be more sophisticated and detailed
- The web does not contain laminated glass, but only one glass element. The current system is non-redundant and are at this stage still theoretical.
- More in-depth analysis of the contact between flange and web with regard to cohesion and temperature. What happens with the adhesives under extreme conditions (High and low temperatures).
- The models capacity is based on the structural properties of glass and does not include the brittleness of the material. Ansys has an own element with specific options when it comes to modelling of concrete, however the values equivalent for glass in regards to this element is not available and more laboratory testing of structural glass should be conducted.
- The analysis doesn't include multiple load cases, which would confirm the trend in increased slip and occurring stresses and give a more affirmative conclusion in regard to the trend lines suggested in table 1.5.
- The recommended improvements that was suggested for the beam was not modelled and tested with the current load case and would be interesting to study in future cases.

Recommendation for Future work

- Study optimization of adhesives in regards to reducing the local stresses on the glass web when the glass and steel is under load.
- In order to verify the model, the best way is to perform laboratory tests.
- Investigate redundancy of laminated glass and how to implement that type of systems in hybrid glass - steel beams.
- Study how the transparency is affected when substituting one glass element with laminated glass.
- Investigate how the manufacturing process is working, and the costs of producing structural glass relative to its substitutes (steel, concrete and timber).
- Investigate the capacity difference between steel beams and hybrid glass – steel beams.

9 Conclusion

- Overall shear did not affect the allowable stresses of the analyzed model.
- The bending stress is the dimensional factor in the current model, increasing the web thickness is the most direct way to increase the capacity of the hybrid – beam without increasing the amount of steel. It leads to higher bending force capacity, higher shear force capacity in the glass and reduced deflection.
- Laboratory tests of similar models should be performed to create a basis on which the model can be verified.
- Increasing area of the steel flanges will increase the moment of inertia. This will increasing the capacity of the beam.
- Alterations of the current intersection can be done to reduce the glass/steel ratio. Substituting the upper steel flange with a glass flange and increasing the thickness of the web is examples of this.
- FE – model 2 was not sophisticated enough to give any certain conclusions regarding the chosen parameters. An uncertainty of the epoxy behavior and occurring slip makes the results somewhat wage, as the contact behavior will affect both shear and bending - stress distribution. I am suggesting that a more advanced FE – modeling of the hybrid configuration should be performed, with laboratory tests of the same beam to verify the model.

References

[1] Ansys, Ansys Help viewer SAS IP, inc, 2016.

[2] Michal Netušil1, Martina Eliášová2, [Hybrid steel-glass beams] Czech Technical University in Prague, Faculty of Civil Engineering, Czech Republic, 2009.

[3] Sharin Loushin, [Choosing and using structural adhesives], Machin design, 2016.

[4] M. Feldmann and R. Kasper, [Guidance for European Structural Design of Glass Components], European commission, 2014.

[5] Ondrej pesek, Jindrich melcher, Milan pilgr, [Numerical Analysis of Hybrid Steel-Glass Beam], Institute of Metal and Timber Structures Brno University of Technology, 2014.

[6] Brian Trenhaile, [Composite (Laminated) Section Analysis Equivalent Area Method], Hawaii marine company, 2010.

[7] Michal Netusil and Martina Eliasova, [Design of the Composite Steel-Glass Beams with Semi-Rigid Polymer Adhesive Joint], Department of Steel and Timber Structures, Faculty of Civil Engineering, Czech Technical University in Prague, 2013.

[8] A. B. Ølgaard, J. H. Nielsen and J. H. Olesen, [Design of mechanically reinforced glass beams modelling and experiments], Structural Engineering International 2, 2009.

[9] M. Netusil and M. Eliasova, [Behaviour of the glued joint in hybrid steel-glass beam], An International Journal for Engineering and Information Sciences 5, 2010.

[10] Glass of Europe, [Main types of glass], received from:
http://www.glassforeurope.com/en/products/main-types-of-glass.php

[11] Pilkington Glass, [Chemistry of glass], received from:
http://www.pilkington.com/pilkington-information/about+pilkington/education/chemistry+of+glass.htm

[12] Klaus-Jürgen Bathe, [finite element procedure], second addition, Massachusetts Institute of Technology, 2014

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