FACULTY OF SCIENCE, TECHNOLOGY AND MEDICINE

Department of Engineering
Bachelor in Engineering – Civil Engineering

Bachelor Thesis

by
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PARAMETER STUDY OF STEEL-TIMBER COMPOSITE STRUCTURES

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Affidavit

I, Lisa Anne Syndikus, declare that this thesis titled "**Parameter study of steel-timber composite structures**" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a Bachelor's degree at the University of Luxembourg
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: L. Syndikus

Date: 03.07.2023

Abstract

Well established construction methods based on massive and material intense designs using mainly concrete and steel are reaching their capacities. The increases importance of sustainability causes the demand for the building sector to change. The carbon footprint of the construction materials and the disassembly options at the end-of-life are the main criteria for the increasingly required sustainable approach in the construction industry.

Steel-timber composite structures can fulfill both requirements, however insufficiently investigated behavior restrain the implementation of this construction method. This thesis therefore proposes an approach for the verification of ultimate limit state and serviceability limit state integrity. Further, different cross sections are investigated to discover any important correlations between the geometry as well as material and the reached bending capacities as well as the behavior of the shear connection.

Finally, this thesis reveals the importance of further research and investigation. As most of the applied computation approaches are based on concrete-steel composite structures, the compatibility with steel-timber composite constructions must get verified. Large scale testing should be conducted for comparison of the theoretical results.

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1. Introduction

The European Commission presented the Green Deal in 2019. Its aim: climate neutrality by 2050. As a first step, the European Union commits towards a reduction of emissions by at least 55% by 2030 compared to 1990 levels. One of the main key factors to reach this goal is the reorientation of the building sector towards a more sustainable future. (European Commission, 2023)

Many approaches are done through certifications that reveal the impact of buildings regarding their complete lifecycle. The DNGB, the International WELL Building Institute and BREEAM are European examples who offer such certifications. Being able to tell the impact of a building and its individual components is important to identify the main problems.

Widely known problems are the high emissions caused by the main construction materials steel and concrete. Modern constructions are mostly built massively even though lighter constructions with similar performance would be less material intensive. However, the industrial revolution and further development caused high raises of costs for human labor and simultaneous reduction of material costs. Material intensive constructions were the consequence.

Today, a new consciousness for sustainability arises and begins to go against these material and emission intensive constructions. Higher performing structures, carbon neutral materials and new construction methods are investigated and implemented. Circular economy with the cradle-to-cradle principle is also one of the mainly discussed points of improvement for the building sector.

Concrete-steel composite structures are already well-used hybrid structures that improved the performance. However, steel and concrete are both carbon intensive materials and their current composite structures cause difficulties with the disassembly at the end of life of the buildings. Therefore, new research started. Steel-timber composite structures replace the carbon and raw material intensive concrete with environmentally friendly timber. The bending capacity of steel-timber composite structures is similar to concrete-steel composite structures and have much better disassembly characteristics. However, timber as a naturally grown material imposes new challenges that need to be investigated. Hence, more research is necessary before widespread implementation of this new construction method. (Romero, et al., 2022)

As steel continues to play an important role of this newly investigated construction method, a solution to reduce the carbon footprint of the material and its fabrication needs to be found. Arcelor Mittal's umbrella brand X-Carb proposes its approach to reduced, low and zero-carbon products. On a long term their blast furnaces shall get replaced with DRI plants and electrical furnaces that are powered by renewable energy. Prior to that, on the short term, decarbonization shall be achieved through proven technologies such as replacing coal with alternative reductants and powering already existing electric arc furnaces with renewable energy. Further, XCarb green steel certificates were introduced as a reaction to the raising interest in low-carbon emissions steel products. XCarb recycled and renewably produced was launched in 2021 and produces since then an increasing range of products in an electric arc furnace using high levels of scalp and 100 percent renewable electricity. By that the regularly high negative environmental impacts of steel got already reduced and continue to be minimized. Steel therefore stays available also for more sustainable building solutions. (ArcelorMittal Europe – Flat Products, 2023)

Based on its so far investigated performance and its realistic small carbon footprint from materials, steel-timber composite structures seem promising for the necessary development of the building sector. Nevertheless, to be able to competitively implement steel-timber composite structures, their behavior must be further analyzed in order to determine general rules and orientations for safe structures.

This thesis will focus on an exemplary structural analysis of a steel-timber composite structure including the ULS and SLS integrity. In the end a comparing overview of further sections and material combinations is investigated to identify possible correlations and remarkable behaviors or regularities.

2. Assumptions for basic material and component behavior

For well elaborated computations the different material behaviors shall be known. Therefore, the later used materials steel and timber will be shortly introduced with their important and defining characteristics. Since the chosen shear connection also influences the behavior of the structure, it shall be introduced as well. Finally, the method used to determine the stress-strain controlled bending resistance and the method used to transfer load slip-curves into an effective shear resistance will be explained.

2.1. Steel

Steel is a well investigated material and widely used in the construction industry. As its industrial production process is well observed and controlled, the material behavior is well predictable. Further, its plastic behavior under both compression and tension make steel a preferred choice of material. For the following computations the simplified material law as shown in Figure 1 will be assumed.

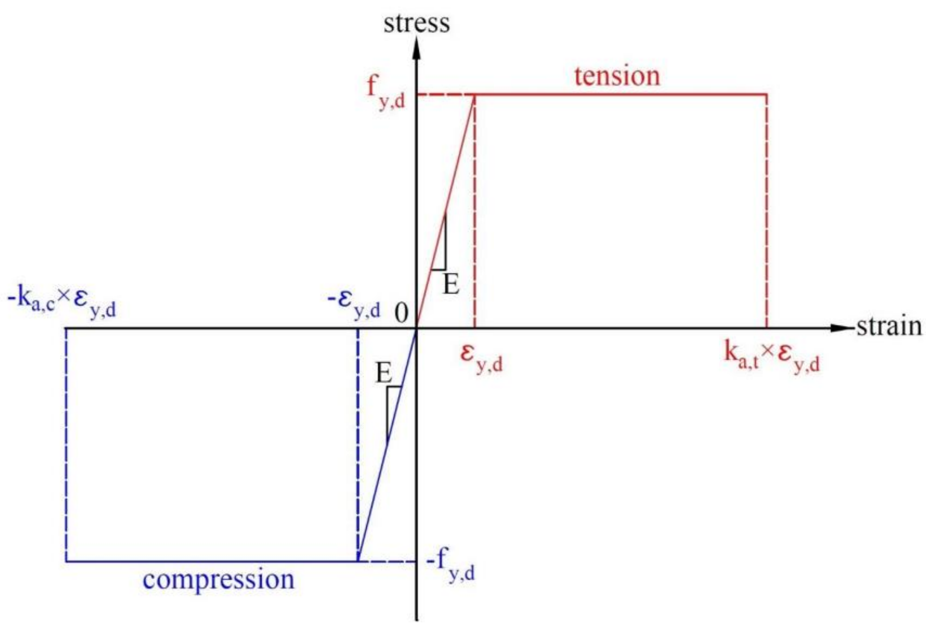


Figure 1: Stress-strain diagram steel (Pelivani, 2022)

Both steel of grad S355 and S460 will be used. Hence, the characteristics of both are presented here:

	S355	S460
Youngs's modulus	$E = 210000\ N/mm^2$	$E = 210000\ N/mm^2$
Design compression and tension strength	$f_{y,d} = \frac{f_y}{\gamma_M} = \frac{355\ N/mm^2}{1} = 355\ N/mm^2$	$f_{y,d} = \frac{f_y}{\gamma_M} = \frac{460\ N/mm^2}{1} = 460\ N/mm^2$
Yield strain	$\varepsilon_{y,d} = \frac{f_y}{E} = \frac{355\ N/mm^2}{210000\ N/mm^2} = 0{,}169\%$	$\varepsilon_{y,d} = \frac{f_y}{E} = \frac{460\ N/mm^2}{210000\ N/mm^2} = 0{,}219\%$
Limiting multiplication factor	$k_{a,c} = k_{a,t} = 89$	$k_{a,c} = k_{a,t} = 89$

Table 1: Characteristics steel

2.2. Timber

Timber in general is a naturally grown, anisotropic and inhomogeneous material with a huge range of variation concerning its mechanical characteristics. There are many different types of construction timber and all of them have individual characteristics. This thesis focuses on laminated veneer lumber (LVL) only, more specific the LVL Kerto Q of Matsä as this is the material used in the analyzed system. LVL Kerto Q panel is composed of 3mm thick coniferous veneers that were selected based on their strengths. Around 20% of the veneers are integrated with a horizontal rotation of 90 degrees relative to the other 80%. All veneers are glued together. The following graphic represents the general appearance of LVL Kerto Q of Matsä:

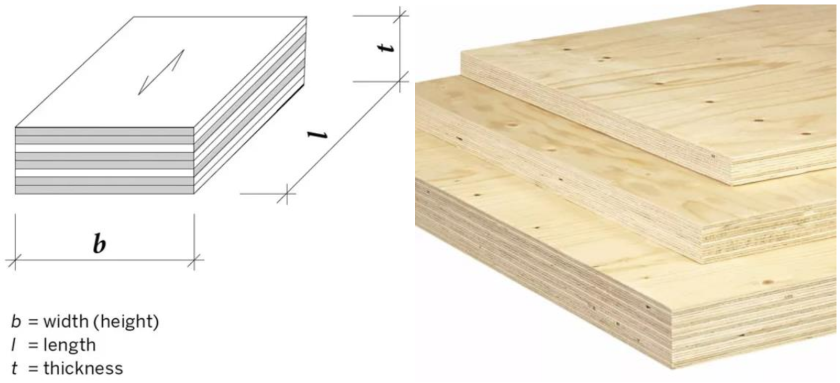


Figure 2: LVL Kerto Q appearance (Metsä Group, 2023)

Most relevant for the analyses is the stress-strain distribution of the LVL Kerto Q. Like any other timber, the LVL Kerto Q reacts plastic in compression and brittle in tension.

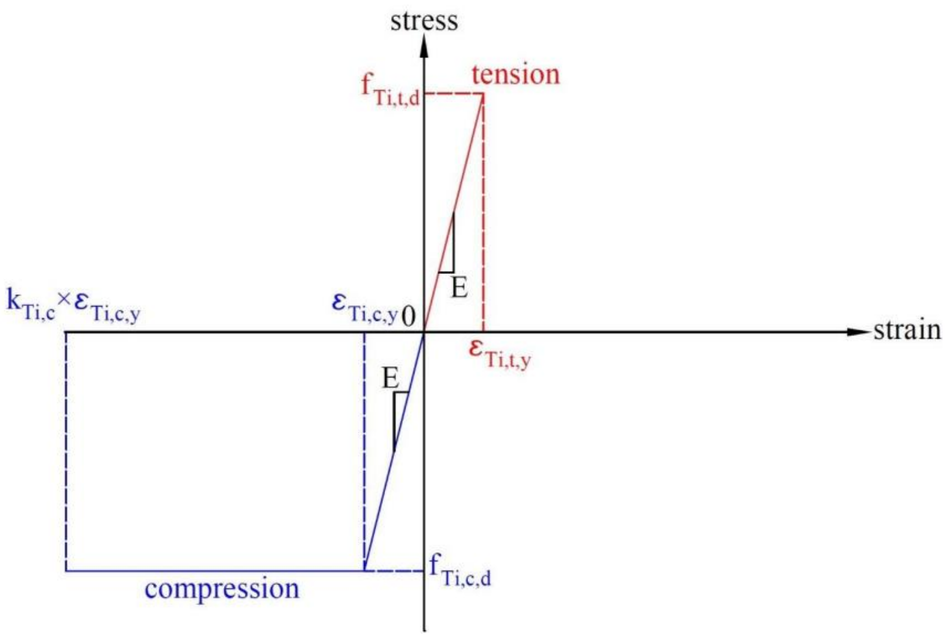


Figure 3: Material law timber (Pelivani, 2022)

The investigated LVL Kerto Q has the following characteristics:

Young's Modulus	$E = 8000 N/mm^2$
Design compression and tension strength	$f_{Ti,c,d} = 0{,}8 \cdot \frac{f_{Ti,c,k}}{\gamma_M} = 0{,}8 \cdot \frac{41\ N/mm^2}{1{,}2} = 27{,}3\ N/mm^2$ $f_{Ti,t,d} = 0{,}8 \cdot \frac{f_{Ti,t,k}}{\gamma_M} = 0{,}8 \cdot \frac{49\ N/mm^2}{1{,}2} = 32{,}7\ N/mm^2$

Yield strain	$\varepsilon_{Ti,c,y} = \frac{f_{Ti,c,d}}{E} = \frac{27{,}3\ N/mm^2}{8000N/mm^2} = 0{,}342\%$ $\varepsilon_{Ti,t,y} = \frac{f_{Ti,t,d}}{E} = \frac{32{,}7\ N/mm^2}{8000N/mm^2} = 0{,}408\%$
Limiting multiplication factor	$k_{Ti,c} = 5$

Table 2: Characteristics LVL Kerto Q

2.3. Shear connection

Composite structures need connections to allow the harmonious interaction of two individual components. Given the development towards circular economy in the building sector, those connections are crucial for the disassembly at the end-of-life phase of any composite structure. Only if the connector allows smooth disassembly, the individual components might be reused. Current research has developed the SCT-3 connector as shown in Figure 4. In comparison with other connector types, the SCT-3 has one of the best performances regarding its load-slip behavior as shown in Figure 5. The connector SCT-3 was hence chosen as connector type for the following computations.

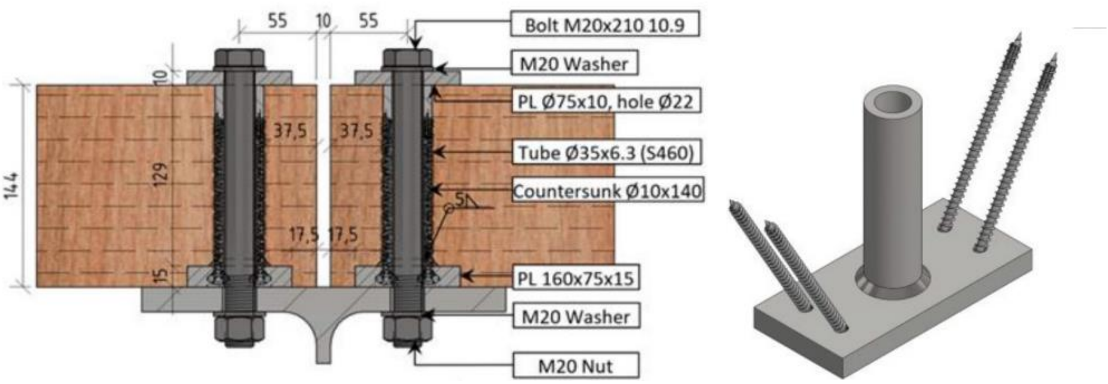


Figure 4: SCT-3 appearance (Nilles, 2023)

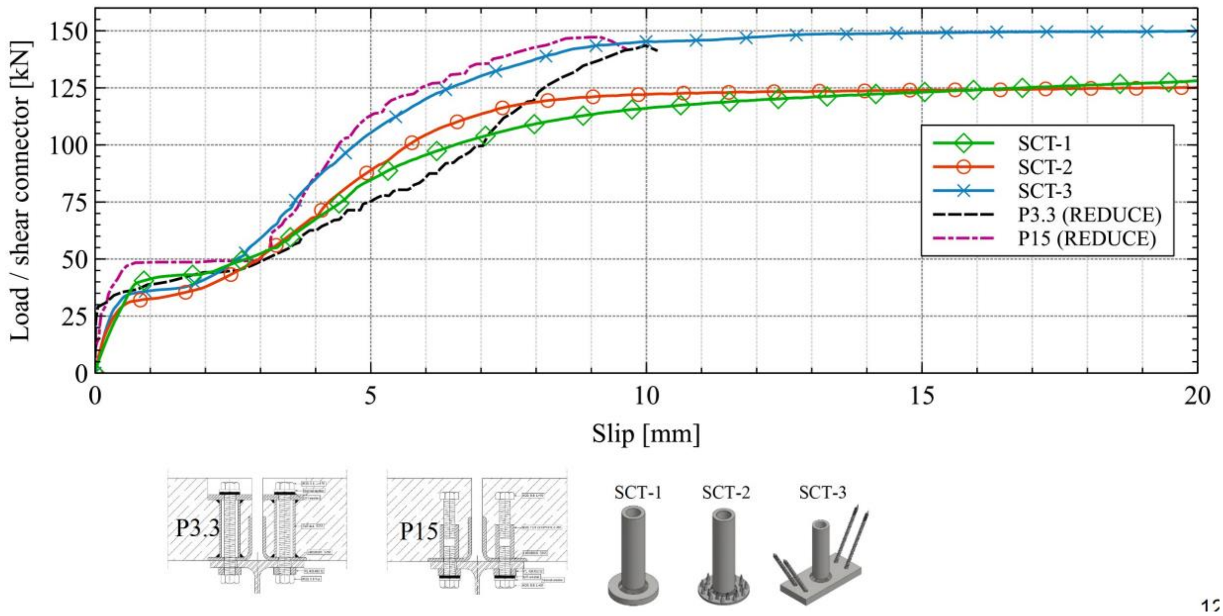


Figure 5: Load-slip diagram comparing different connectors (Nilles, 2023)

Important for further computations is the load-slip curve of the given connector. The in Figure 6 presented curve is result of experimental testing and will therefore be subject of transformation into a design load-slip curve. This transformation is part of the determination of the effective shear resistance of the connector type and will be explained and done in the following chapters.

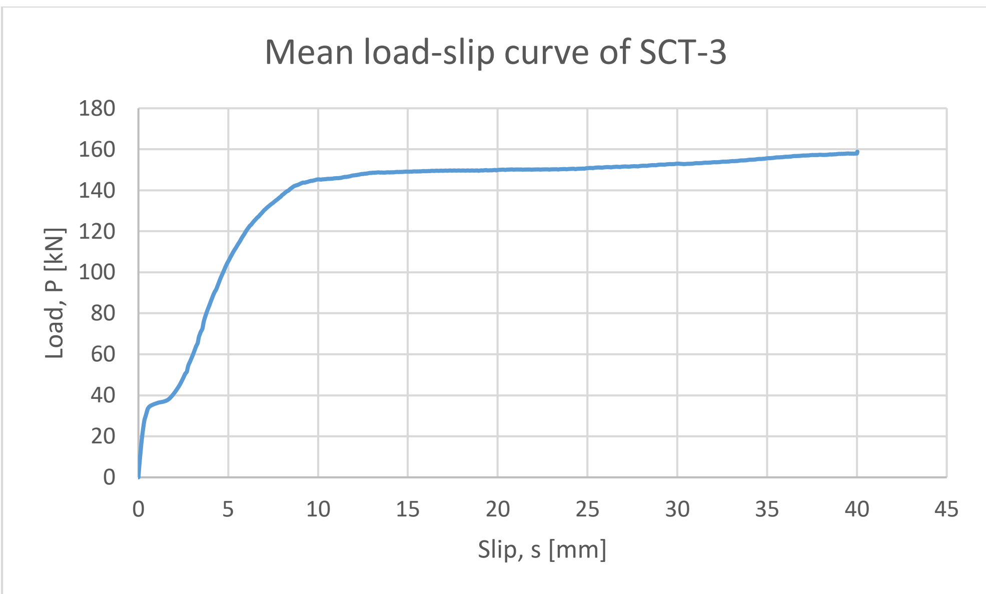


Figure 6: Mean load-slip curve of SCT3

2.4. Algorithm to determine stress-strain controlled bending resistance

The hereinafter applied calculation model is based on the approach investigated recently as part of the ongoing research under the name Prefa-SeTi at the University of Luxemburg. For this thesis the application of the calculation model is a tool and will therefore only be briefly described for general understanding. (Pelivani, 2022)

The calculation model assumes the Bernoulli-Euler Beam Theory for bending and a linear strain distribution for the section. However, depending on whether there is a full, partial, or no shear connection, the characteristics of the calculation vary slightly. Each shear connection case will be explained individually. For all shear connection cases, the section is divided into lamellas. (Pelivani, 2022)

Full shear connection

In case of full shear connection, the strain distribution is assumed to be continuous. To determine the respective bending resistances an equilibrium of compressive and tensile forces is to be found. Initiating the calculations with the maximal possible strain slope, an iteration is applied until the sum of forces reaches zero. The bending resistance is then determined by the sum of moments around the point at the very top of the section. (Pelivani, 2022)

No shear connection

In case of no shear connection, the strain distribution is split into two parts, one for the timber section and one for the steel section. However, as a constraint, the two separate distributions must be parallel. Different from the full shear connection, an equilibrium of compressive and tensile forces is to be found for each of the two parts separately. Herby, the strain distribution is constrained by the maximal curvature of timber. Having found the equilibrium state, the bending resistance is determined by the sum of moments around the point at the very top of the section. (Pelivani, 2022)

Partial shear connection

In case of partial shear connection, the strain distribution is again split into two parallel parts, one for the timber section and one for the steel section. The partial shear connection is characterized by the degree of shear connection (full shear connection: η=1; no shear connection: η=0; partial full shear connection: 0<η<1). Other than previously seen, the bending resistance for partial shear connection is here given by a M-η-distribution. This distribution is determined by an iterative process starting under the conditions of full shear connection and then approaching step by step the conditions of no shear connection. An increase of iteration steps results in a more precise M-η-distribution. (Pelivani, 2022)

2.5. Algorithm to transfer load-slip curves into an effective shear resistance

The hereinafter described algorithm was developed for Eurocode 4 suitable structures (steel-concrete composite structures). However, the same approach will be assumed for steel-timber composite structures while respecting certain adjustments due to material behavior. Possible derivations are to be investigated.

Like the previously described determination of the stress-strain controlled bending resistance, this algorithm is also viewed as a tool and is therefore only described briefly for general understanding.

The algorithm is composed of the following steps (Kozma, et al., 2020):

1. Selection of shear connector distribution and number of shear connections
2. Assumption of slip distribution and determination of slip values
3. Determination of shear forces based on load-slip curve
4. Determination of average design shear force P_{av}
5. Determination of k_{flex}
6. Determination of effective design shear resistance $P_{Rd,eff}$

The herewith obtained effective design shear resistance then is used to determine the degree of shear connection of the given systems.

3. Structural Analysis of a beam based on experimental testing S355

The here chosen system is based on experimental testing that will follow this thesis. This allows to compare the computed results (i.e., theoretical behavior) with the results of experimental testing (i.e., real behavior). In addition to this system, similar systems will be subject of this analysis.

3.1. System

The analyzed system is a simple spam beam and assumed to be part of an office building. Figure 7 represents the simple spam beam and the load distribution.

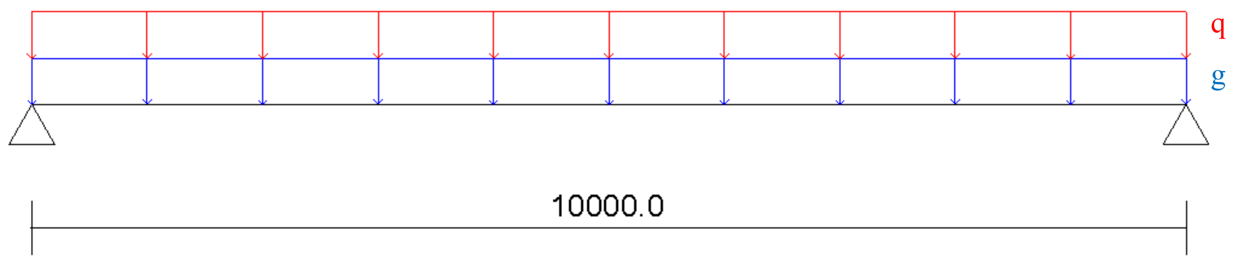


Figure 7: Analyzed system with loading distribution

3.2. Section and material properties

The section of the given system is shown in Figure 8. The top part is a timber slab of LVL Kerto Q and the bottom part is an IPE 400 steel beam made of a S355 graded steel.

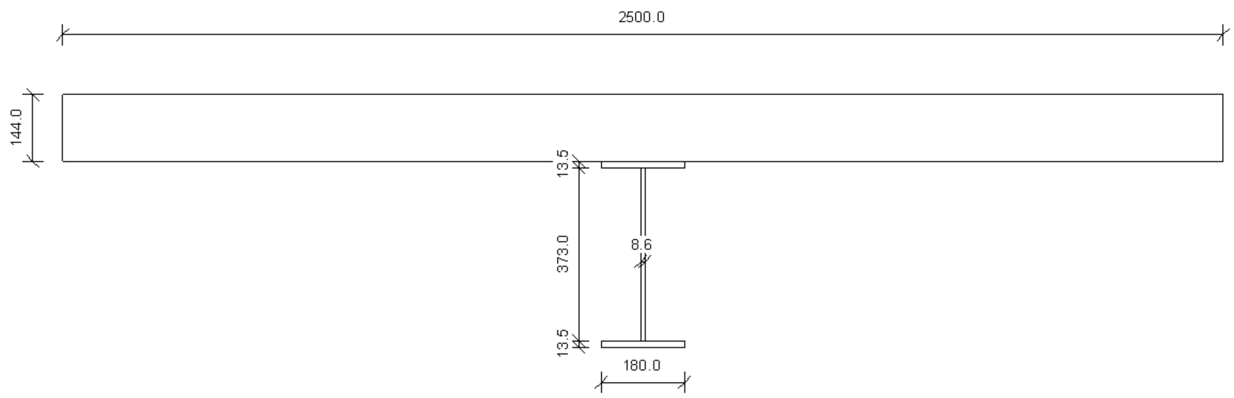


Figure 8: Section of analyzed system

The timber slap and the steel beam are connected through equidistantly distributed connectors as shown in Figure 9. The structure has 30 connectors on each side of the web with a transversal spacing of 110mm, hence, there are 60 connectors in total. The distance from the edge of the beam to the first connector is equal to 106,25mm. The longitudinal spacing between the connectors is equal to 337,5mm.

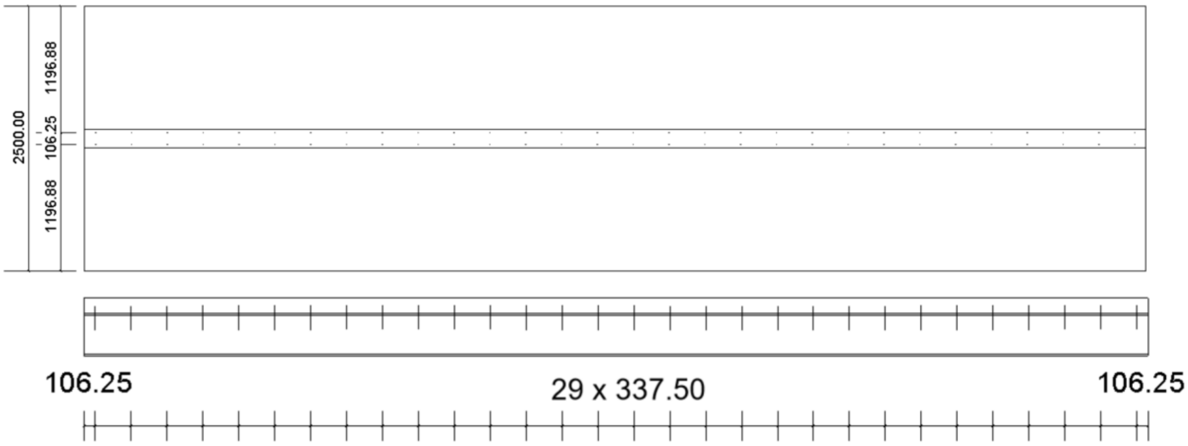


Figure 9: Distribution of connectors

LVL Kerto Q has the following characteristics:

Young's Modulus	$E = 8000 N/mm^2$
Design compression and tension strength	$f_{Ti,c,d} = 0{,}8 \cdot \frac{f_{Ti,c,k}}{\gamma_M} = 0{,}8 \cdot \frac{41\ N/mm^2}{1{,}2} = 27{,}3\ N/mm^2$ $f_{Ti,t,d} = 0{,}8 \cdot \frac{f_{Ti,t,k}}{\gamma_M} = 0{,}8 \cdot \frac{49\ N/mm^2}{1{,}2} = 32{,}7\ N/mm^2$
Yield strain	$\varepsilon_{Ti,c,y} = \frac{f_{Ti,c,d}}{E} = \frac{27{,}3\ N/mm^2}{8000 N/mm^2} = 0{,}342\%$ $\varepsilon_{Ti,t,y} = \frac{f_{Ti,t,d}}{E} = \frac{32{,}7\ N/mm^2}{8000 N/mm^2} = 0{,}408\%$
Limiting multiplication factor	$k_{Ti,c} = 5$

Table 3: Material characteristics of LVL Kerto Q

Steel of the steel grade S355 has the following characteristics:

Youngs's modulus	$E = 210000\ N/mm^2$
Design compression and tension strength	$f_{y,d} = \frac{f_y}{\gamma_M} = \frac{355\ N/mm^2}{1}$ $= 355\ N/mm^2$
Yield strain	$\varepsilon_{y,d} = \frac{f_y}{E} = \frac{355\ N/mm^2}{210000\ N/mm^2}$ $= 0{,}169\%$

Limiting multiplication factor	$k_{a,c} = k_{a,t} = 89$

Table 4: Material characteristics of steel S355

3.3. Loading

As the beam is assumed to be part on an office building, the loading is assumed to be composed of dead loads given by the structure itself as well as by the assumed flooring. In addition, a payload which includes partition walls shall be considered.

Deadload 1 (given by section properties)	
$g_{1,k}$	$= 66{,}30$ kg/m · 10/1000 + 73,44 kg/m² · 2,5m · 10/1000 = 0,663 + 1,836 = 2,5 kN/m
Deadload 2 (for flooring)	
$g_{2,k}$	= 1 kN/m² · 2,5m = 2,5 kN/m
Payload (assuming an office building, including partition walls)	
q_k	= 5 kN/m² · 2,5m = 12,5 kN/m

Table 5: Computation of loads

In accordance with EC 1, the load combination for ULS integrity shall be done with safety factors depending on the load type. The deadloads are multiplied with γ_g=1,35 and the payload is multiplied with γ_q=1,5. Altogether the load combination results as follows:

Load combination ULS	
e	$= 1{,}35 \cdot (g_{1,k} + g_{2,k}) + 1{,}5 \cdot q_k$ = 1,35 · (2,5 kN/m + 2,5 kN/m) + 1,5 · 12,5 kN/m = 6,75 kN/m +18,75kN/m = 25,5 kN/m

Table 6: Computation of load combination

3.4. Reactions

With the given characteristics, the reactions of the system are calculated, and each distribution is illustrated:

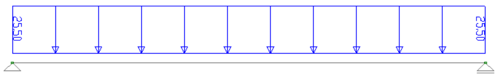
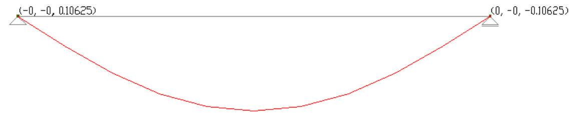
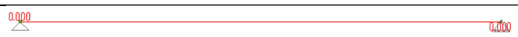
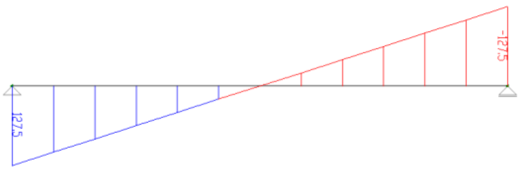
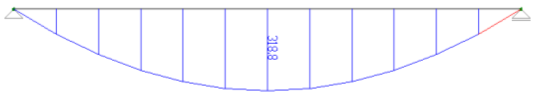
Geometry		
		
Deformation		
		
Horizontal forces		
N	= 0 kN	
Vertical forces		
A=B= $V_{z,\,max}$	= 25,5 kN/m · 10m / 2 = 127,5 kN	
Bending moment		
M_{max}	= 25,5 kN/m · 10m · 10m / 8 = 318,75 kNm	

Table 7: Reaction of the system

3.5. ULS integrity

To determine the ULS integrity of the structure, first the Pelivani Algorithm is applied to receive the M-η-distribution. Then the Kozma Algorithm is applied to determine k_{flex} and $P_{R,\,eff}$. Given these values, the individual η-value is calculated and then used to find the applicable bending resistance. Finally, the bending resistance shall be compared to the maximal bending moment.

3.5.1. Stress strain controlled bending moment

The moment-eta distribution is obtained by the previously explained Romero/Pelivani Algorithm. The algorithm was applied through the MATLAB App specially created for timber-steel composite structures. To obtain the wanted results first, all geometry defining measurements, material properties and strain limits must be entered into the application. Then the stress-strain distribution as well as an illustration of the geometry get displayed. For the partial shear connection, a specific number of steps for the rotation about point A and a specific number of steps for the rotation about point B must be put in. To compute all results, the "solve all" option is used.

The input for geometry, material properties and strain limits:

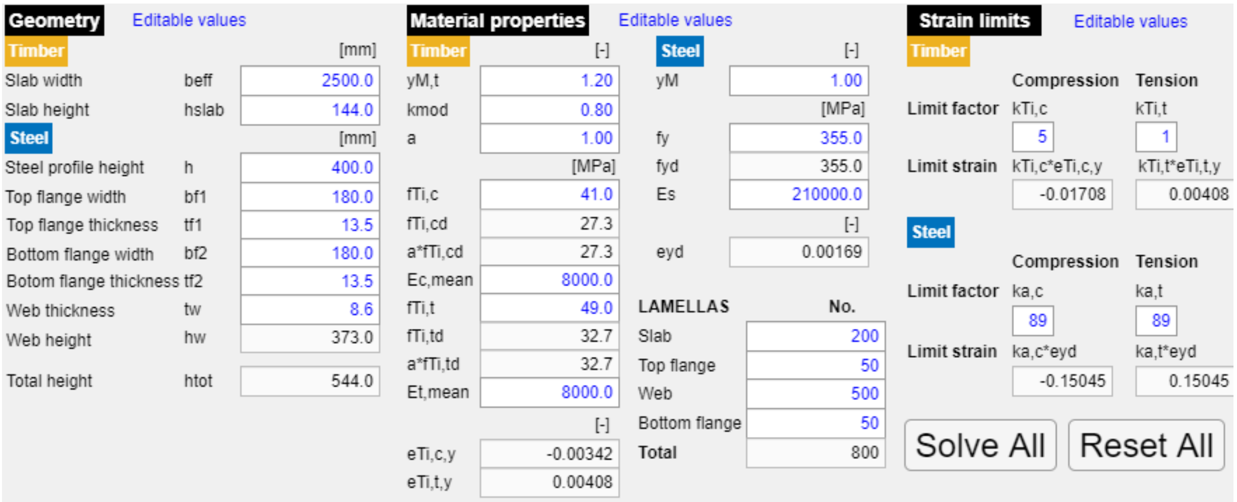


Figure 10: IPE400, S355, t=2500x144: geometry, material properties, strain limits

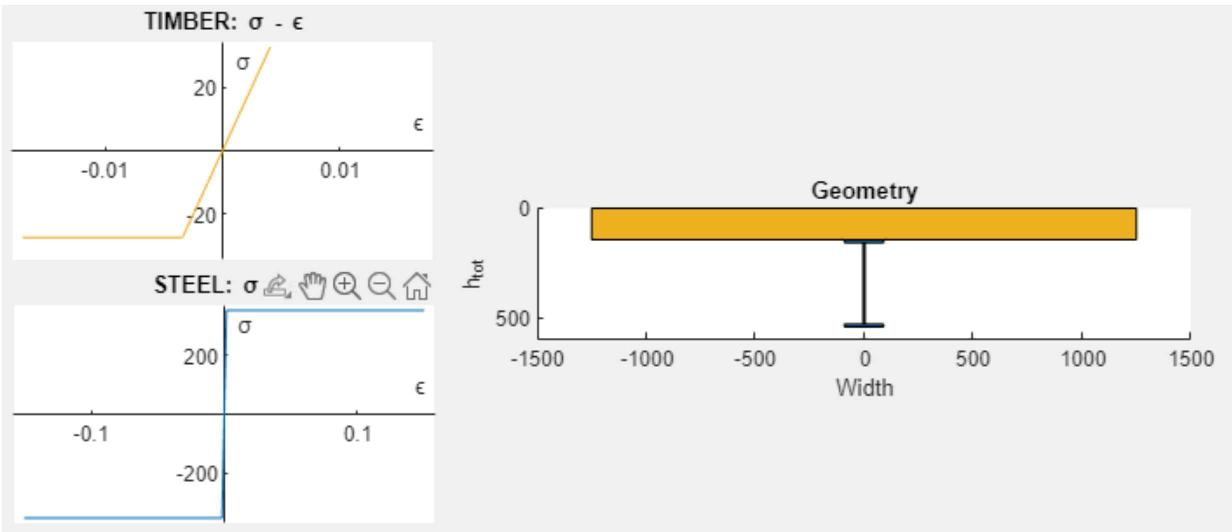


Figure 11: IPE400, S355, t=2500x144: stress-strain distribution, geometry illustration

Results for full shear connection:

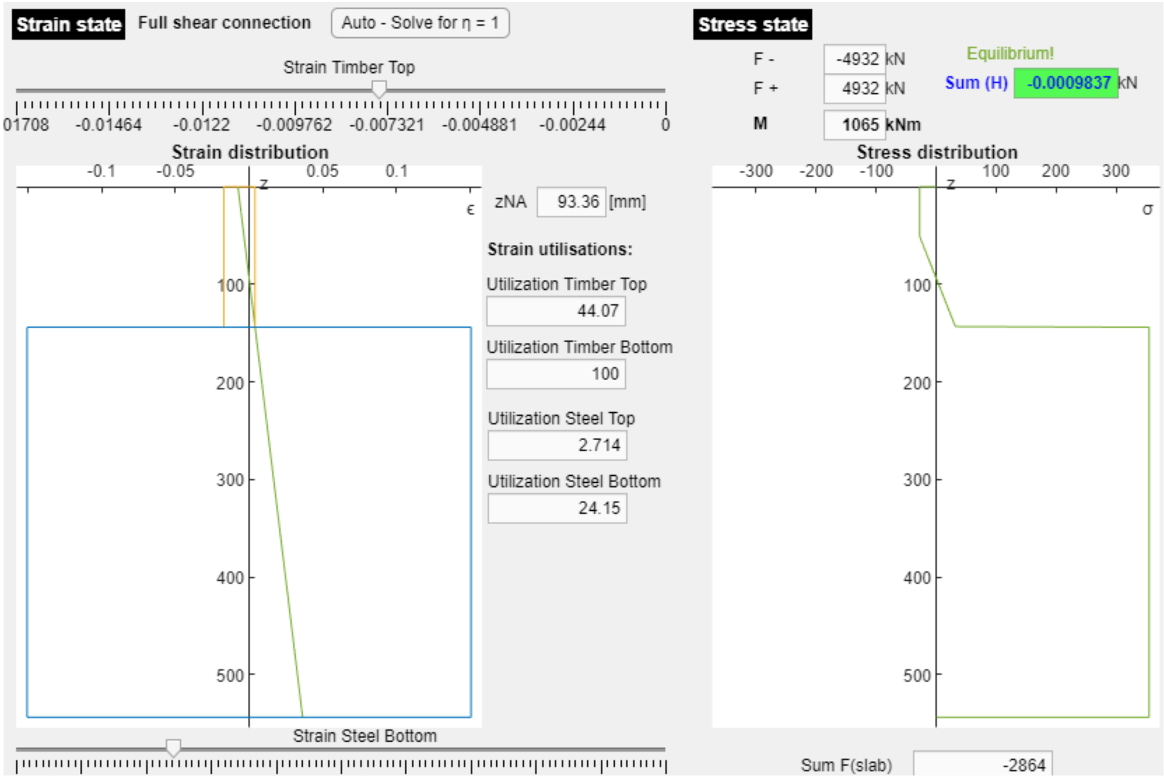


Figure 12: IPE400, S355, t=2500x144: Full shear connection - results

Results for no shear connection:

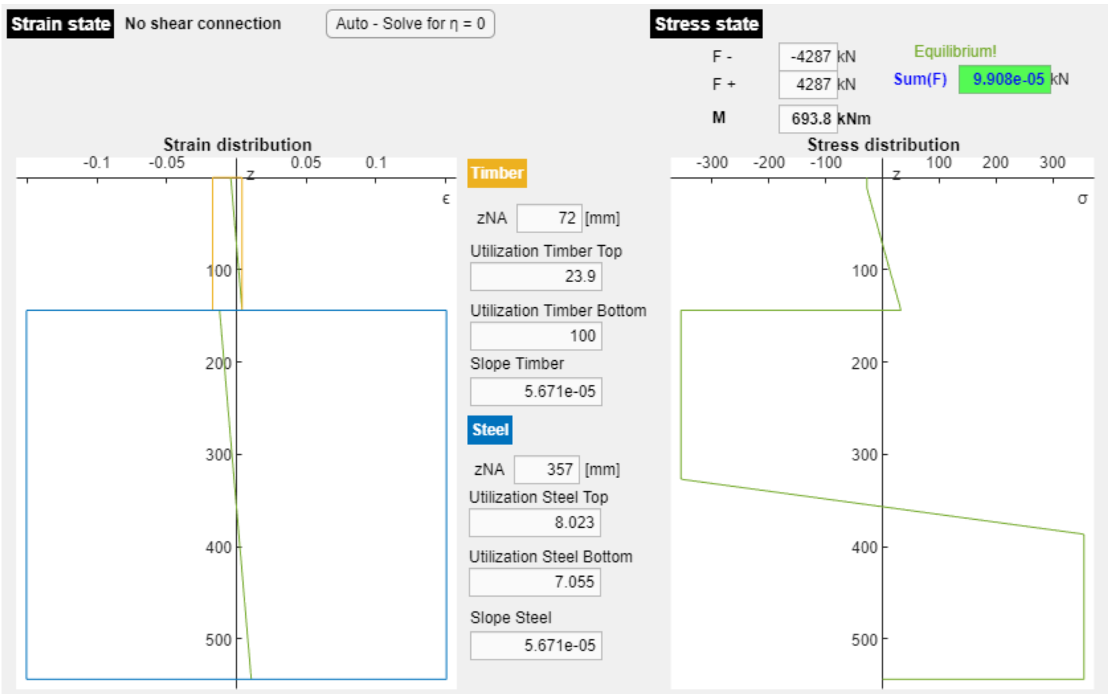


Figure 13: IPE400, S355, t=2500x144: No shear connection - results

Results for partial shear connection:

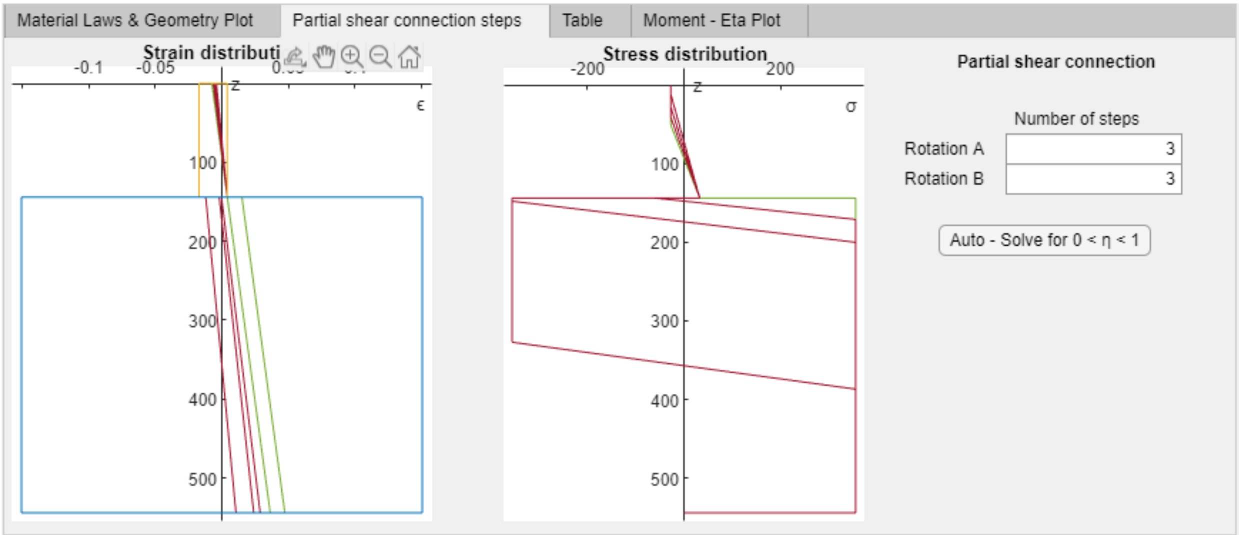


Figure 14: IPE400, S355, t=2500x144: Partial shear connection- computation steps

Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0075	0.0041	0.0041	0.0363	-2.8641e+03	2.8641e+03	-9.8374e-04	1	1.0650e+03
1	-0.0075	0.0041	0.0150	0.0473	-2.8641e+03	2.8641e+03	-9.8374e-04	1	1.0650e+03
2	-0.0075	0.0041	0.0150	0.0473	-2.8641e+03	2.8641e+03	-9.8374e-04	1	1.0650e+03
3	-0.0075	0.0041	0.0150	0.0473	-2.8641e+03	2.8641e+03	-9.8374e-04	1	1.0650e+03
4	-0.0064	0.0041	-2.7841e-04	0.0288	-2.0985e+03	2.0975e+03	-0.9993	0.7327	1.0100e+03
5	-0.0052	0.0041	-0.0019	0.0239	-1.1443e+03	1.1433e+03	-0.9909	0.3995	931.6159
6	-0.0041	0.0041	-0.0121	0.0106	78.4320	-79.4184	-0.9864	-0.0274	693.4040

Figure 15: IPE400, S355, t=2500x144: Partial shear connection - table

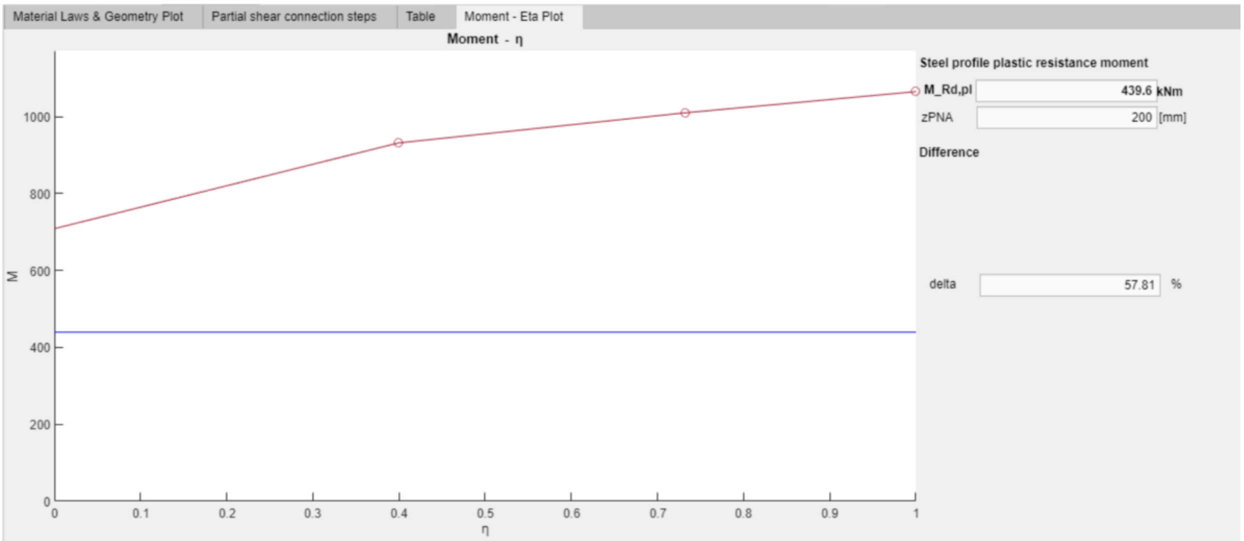


Figure 16: IPE400, S355, t=2500x144: Partial shear conection - M-eta-distribution

It shall be noted that a more detailed M-eta-distribution would have been preferable, however the MATLAB application could not compute more steps for this specific cross section with the given properties.

3.5.2. Effective shear resistance of connectors

Step 1: Selection of shear connector distribution and number of shear connections

The analyzed system has the shear connector distribution as shown in Figure 9. Each row has 30 connectors, hence in total there are 60 connectors.

Step 2: Assumption of slip distribution and determination of slip values

The slip distribution is assumed to be a cosine function where the end slip values equal to 6mm and is shown in Figure 17. The function equals to:

$$s(x) = 6 \cdot cos\left(\frac{x \cdot \pi}{10000}\right)$$

where x describes the distance from the end of the beam in mm.

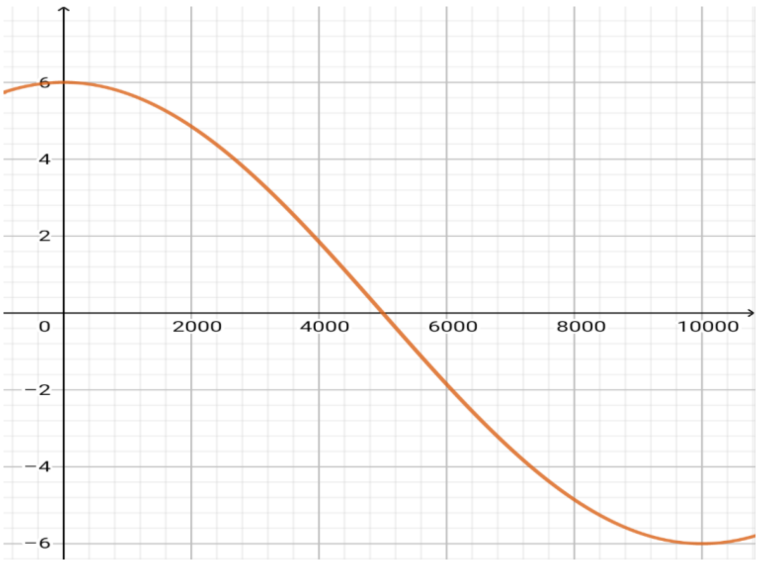


Figure 17: Slip distribution

Given this information the slip values of each connector can be determined.

Step 3: Determining shear forces based on load-slip curve

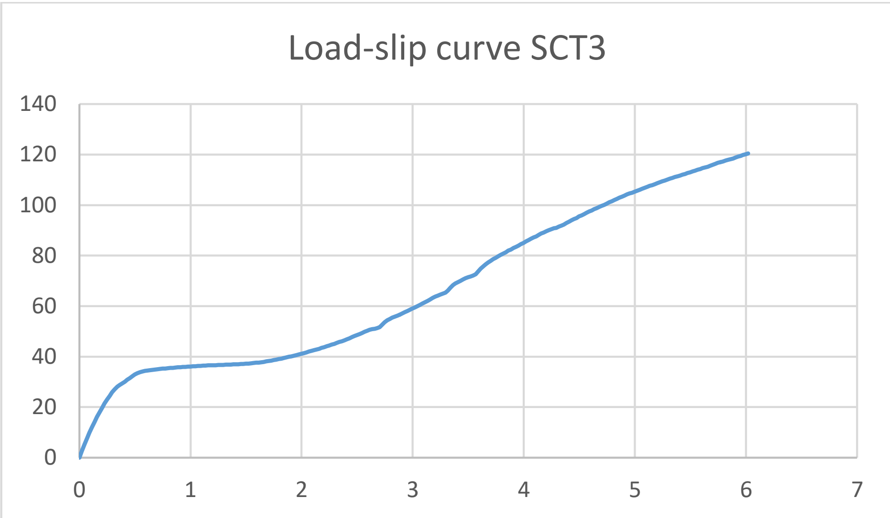


Figure 18: Load-slip curve SCT3

Table 8 shows the slip values and their according shear forces P_i. Further the values $P_{i,k}$ and $P_{i,d}$ are determined by:

$$P_{i,k} = Pi \cdot 0{,}9 \qquad P_{i,d} = \frac{P_{i,k}}{1{,}25} \tag{1}$$

n -	x mm	s mm	P_i kN	$P_{i,k}$ kN	$P_{i,d}$ kN
1	106,25	5,99666114	120,149013	108,134111	90,1117595
2	443,75	5,94184936	119,186818	107,268137	89,3901138
3	781,25	5,82036887	117,597853	105,838068	88,1983898
4	1118,75	5,63358272	114,911467	103,42032	86,1836003
5	1456,25	5,38358668	111,390291	100,251261	83,5427179
6	1793,75	5,07318575	106,450168	95,8051515	79,8376262
7	2131,25	4,7058627	99,6869459	89,7182513	74,7652094
8	2468,75	4,28573895	90,8513056	81,766175	68,1384792
9	2806,25	3,81752838	80,8754058	72,7878652	60,6565543
10	3143,75	3,3064844	65,3022423	58,7720181	48,9766817
11	3481,25	2,75834103	53,5962744	48,236647	40,1972058
12	3818,75	2,17924853	43,1477534	38,8329781	32,3608151
13	4156,25	1,57570445	37,4630231	33,7167208	28,0972673
14	4493,75	0,95448066	35,88514	32,296626	26,913855
15	4831,25	0,3225474	27,1323813	24,4191432	20,349286
	5000	0	0	0	0
					917,719561

Table 8: Shear forces based on load-slip curve

Representing S_i and $P_{i,d}$ in a diagram shows the design load-slip curve shown in Figure 19.

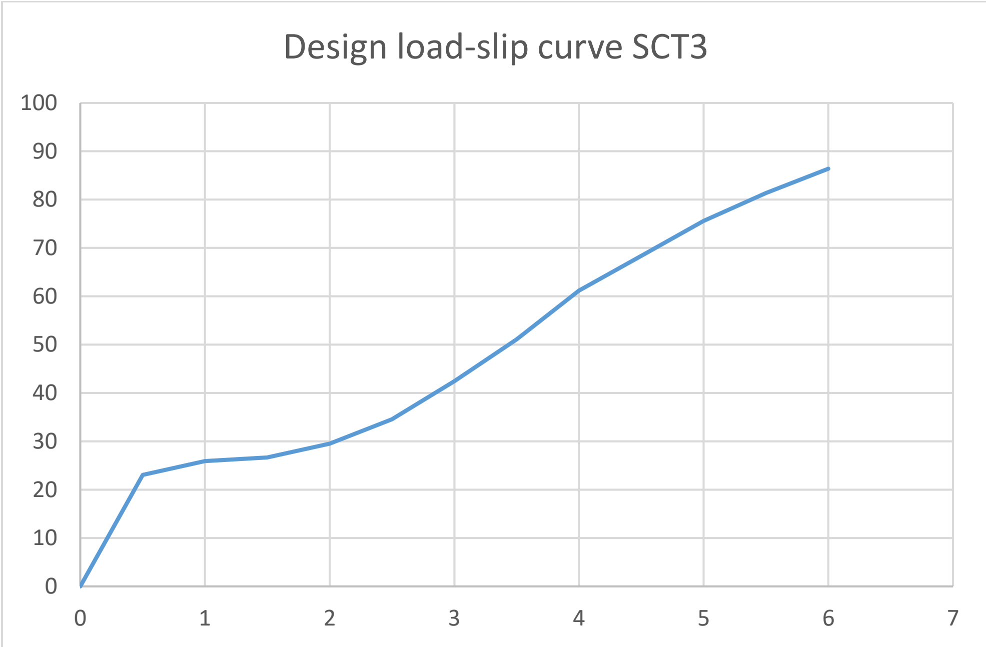


Figure 19: Design load-slip curve SCT3

Step 4: Determining average design shear force $P_{av,d}$

The average design shear force $P_{av,d}$ is determined by:

$$P_{av,d} = \frac{1}{15}\sum_{i=1}^{15} P_{i,d} = \frac{1}{15} \cdot 917{,}72kN = \mathbf{61{,}18kN} \tag{2}$$

Step 5: Determination of k_{flex}

The factor k_{flex} is determined by:

$$k_{flex} = \frac{P_{av,d}}{P_{1,d}} = \frac{61{,}81kN}{90{,}11kN} = \mathbf{0{,}6789} \tag{3}$$

Step 6: Determination of effective design shear resistance $P_{Rd,eff}$

The effective design shear resistance is determined by:

$$P_{Rd,eff} = k_{flex} \cdot P_{1,d} = 0{,}6789 \cdot 917{,}72kN = \mathbf{61{,}18kN} \tag{4}$$

3.5.3. Ultimate limit state integrity (ULS)

Before being able to check the ultimate limit state integrity the degree of shear connection of this composite beam must be identified. The degree of shear connection is determined by the quotient of horizontal shear resistance of the full shear connection $N_{c,f}$ and the shear resistance of all connectors together N_c.

$$\frac{N_c}{N_{c,f}} = \frac{30 \cdot 61{,}18kN}{4932kN} = \frac{1835{,}4kN}{4932kN} = 0{,}372 \tag{5}$$

η= 0,372

Based on the degree of shear connection, the applicable moment resistance can be determined. As the M-η-distribution in the example is approached through several linear sections, the determination must be done by a linear interpolation. The surrounding values of η= 0,372 are used as values for the interpolation.

$$M_{pl} = \frac{963{,}4 - 931{,}6}{-0{,}0274 - 0{,}3995} \cdot (0{,}372 - 0{,}7327) + 931{,}6 = 916{,}3kNm \tag{6}$$

The ULS integrity is proofed by:

$$M_{Rd} = 916{,}3kNm > 318{,}7kNm = M_{Ed} \tag{7}$$

Additionally, the degree of utilization is calculated to show how well the cross section is used:

$$\frac{M_{Ed}}{M_{Rd}} = \frac{318{,}7kNm}{916{,}3kNm} = 0{,}348 \tag{8}$$

A degree of utilization of 0,325 is very low. Usually, a degree of > 0,85 is preferred for economic reasons. It would therefore be advisable to choose a less performing cross section.

3.6. Verification of results

As the used application to determine the M- η-distribution was just recently developed, computation errors are more likely to occur. To prevent false results, the results of full shear connection and an exemplary partial shear connection result will be checked. In both cases the obtained ε-distributions are used as basis of the verifying calculations.

The general process of the hand calculations gets applied both for the results of full shear connection and the exemplary partial shear connection with η=0,7327 and comprises the following steps:

1. Determination of a suitable lamella distribution
2. Determination of area and lever arm of each lamella
3. Assignation of ε-values

4. Determination of applicable σ-values by using stress-strain-diagrams of the materials
5. Calculation of inner forces
6. Calculation of inner moments
7. Summing up inner forces and moments
8. Comparison with results obtained from application

For a better understanding each step shall be further explained and applied as far as generally possible. The results for full shear connection and the exemplary partial shear connection with η=0,7327 are situated at the end of this explanation.

1. Determination of a suitable lamella distribution

The high number of lamellas used in the application would be too much for a quick verification of results. The number of lamellas is therefore reduced from a total of 800 to 25. Their distribution (5-5-10-5) is shown in the Figure 20.

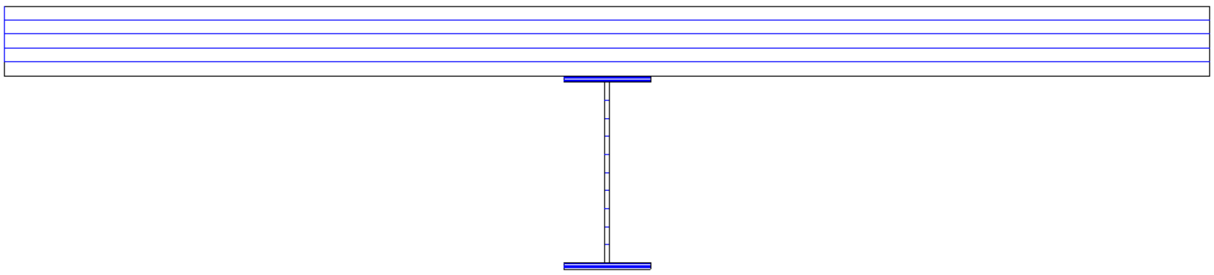


Figure 20: Lamella distribution of section

2. Determination of area and lever arm of each lamella

The area A_i of each lamella is obtained by the multiplication of their height and their lengths.
The lever arms z_i are determined from the very top (z = 0mm) of the section straight down to the center of each lamella.

3. Assignation of ε-values

Based on the values obtained from the application, the ε-values for z = 0 mm (timber), z = 144 mm (timber and steel) and z = 544 mm (steel) are used to find the ε-values of each lamella. The determination is done by linear interpolation in between z = 0 mm and z = 144 mm (timber) for the first five lamellas and in between z = 144 mm (steel) and z = 544 mm for the remaining 20 lamellas due to the change of material. This differentiation is only important for the partial shear connection as its strain distribution is not continuous but composed of two separate parallel linear distributions.

4. Determination of applicable σ-values by using stress-strain-diagrams of the materials

Based on the stress-strain diagrams of each material the σ-values are determined.
The following rules apply:

LVL Kerto Q	For ε > 0,00408	-
	For 0,00408 < ε < -0,00342	σ = E·ε
	For ε > -0,00342	σ = -27,3N/mm²
Steel S355	For ε > 0,00169	σ = 355N/mm²
	For 0,00169 < ε < -0,00169	σ = E·ε
	For ε > -0,00169	σ = -355N/mm²

Table 9: Determing rules of stress-strain distribution

5. Calculation of inner forces

The inner forces are obtained by the multiplication of stress times area.

$$F_i = \sigma_i \cdot A_i \tag{9}$$

6. Calculation of inner moments

The inner moments are obtained by the multiplication of inner forces times lever arms.

$$M_i = F_i \cdot z_i \tag{10}$$

7. Summing up inner forces and moments

The sum of inner forces and the sum of inner moments shall be calculated. The sum of inner forces should be equal to 0 for an equilibrium.

8. Comparison with results obtained from application

For comparison, the sum of inner moments shall be divided by the previously obtained result of the application.

The results of both verifications are shown as tables (Table 10 and Table 11). The final value for accuracy shows how close the manual computations got to the results of the application. A value equal to one would imply perfect agreement.

Full shear connection

	Lamella	A_i mm²	Z_i mm	ε -	σ N/mm²	F_i kN	M_i kNm
	-	-	0,00	-0,007527	-	-	-
timber	1,00	72000,00	14,40	-0,006366	-27,30	-1965,60	-28,30
	2,00	72000,00	43,20	-0,004045	-27,30	-1965,60	-84,91
	3,00	72000,00	72,00	-0,001724	-13,79	-992,79	-71,48
	4,00	72000,00	100,80	0,000598	4,78	344,36	34,71
	5,00	72000,00	129,60	0,002919	23,35	1681,51	217,92
	-	-	144,00	0,004080	-	-	-
	-	-	144,00	0,004083	-	-	-
steel flange	6,00	486,00	145,35	0,004192	355,00	172,53	25,08
	7,00	486,00	148,05	0,004410	355,00	172,53	25,54
	8,00	486,00	150,75	0,004627	355,00	172,53	26,01
	9,00	486,00	153,45	0,004845	355,00	172,53	26,47
	10,00	486,00	156,15	0,005063	355,00	172,53	26,94
steel web	11,00	320,78	176,15	0,006675	355,00	113,88	20,06
	12,00	320,78	213,45	0,009683	355,00	113,88	24,31
	13,00	320,78	250,75	0,012690	355,00	113,88	28,55
	14,00	320,78	288,05	0,015697	355,00	113,88	32,80
	15,00	320,78	325,35	0,018705	355,00	113,88	37,05
	16,00	320,78	362,65	0,021712	355,00	113,88	41,30
	17,00	320,78	399,95	0,024719	355,00	113,88	45,55
	18,00	320,78	437,25	0,027727	355,00	113,88	49,79
	19,00	320,78	474,25	0,030710	355,00	113,88	54,01
	20,00	320,78	511,85	0,033742	355,00	113,88	58,29
steel flange	21,00	486,00	531,85	0,035354	355,00	172,53	91,76
	22,00	486,00	534,55	0,035572	355,00	172,53	92,23
	23,00	486,00	537,25	0,035789	355,00	172,53	92,69
	24,00	486,00	539,95	0,036007	355,00	172,53	93,16
	25,00	486,00	542,65	0,036225	355,00	172,53	93,62
	-	-	544,00	0,036334	-	-	-
				Sums:	Manual	-34,06	1053,14
					Application	0	1065,00
						Accuracy:	0,98886

Table 10: Computation results for verification of full shear connection

Exemplary partial shear connection with η= 0,7327

	Lamella	A_i	Z_i	ε	σ	F_i	M_i
		mm²	mm	-	N/mm²	kN	kNm
	-	-	0,00	-0,006400	-	-	-
timber	1,00	72000,00	14,40	-0,005352	-27,30	-1965,60	-28,30
	2,00	72000,00	43,20	-0,003256	-26,05	-1875,46	-81,02
	3,00	72000,00	72,00	-0,001160	-9,28	-668,16	-48,11
	4,00	72000,00	100,80	0,000936	7,49	539,14	54,34
	5,00	72000,00	129,60	0,003032	24,26	1746,43	226,34
	-	-	144,00	0,004080	-	-	-
	-	-	144,00	-0,000278	-	-	-
steel flange	6,00	486,00	145,35	-0,000180	-37,86	-18,40	-2,67
	7,00	486,00	148,05	0,000016	3,36	1,63	0,24
	8,00	486,00	150,75	0,000212	44,58	21,67	3,27
	9,00	486,00	153,45	0,000409	85,80	41,70	6,40
	10,00	486,00	156,15	0,000605	127,02	61,73	9,64
steel web	11,00	320,78	176,15	0,002059	355,00	113,88	20,06
	12,00	320,78	213,45	0,004770	355,00	113,88	24,31
	13,00	320,78	250,75	0,007482	355,00	113,88	28,55
	14,00	320,78	288,05	0,010193	355,00	113,88	32,80
	15,00	320,78	325,35	0,012905	355,00	113,88	37,05
	16,00	320,78	362,65	0,015617	355,00	113,88	41,30
	17,00	320,78	399,95	0,018328	355,00	113,88	45,55
	18,00	320,78	437,25	0,021040	355,00	113,88	49,79
	19,00	320,78	474,25	0,023729	355,00	113,88	54,01
	20,00	320,78	511,85	0,026463	355,00	113,88	58,29
steel flange	21,00	486,00	531,85	0,027917	355,00	172,53	91,76
	22,00	486,00	534,55	0,028113	355,00	172,53	92,23
	23,00	486,00	537,25	0,028309	355,00	172,53	92,69
	24,00	486,00	539,95	0,028506	355,00	172,53	93,16
	25,00	486,00	542,65	0,028702	355,00	172,53	93,62
	-	-	544,00	0,028800	-	-	-
				Sums:	Manual	-113,90	995,28
					Application	0,00	1010,00
						Accuracy:	0,9854

Table 11: Computation results for verification of partial shear connection η= 0,7327

Both verification computations show satisfactory results. The application's computations seem trustworthy.

3.7. Serviceability limite state integrity (SLS)

In addition to the ULS, the SLS integrity is also mandatory. While the ULS focuses on the minimum requirement for structural safety, the SLS considers the comfort of the user under regular conditions. Here the focus is put on the elastic deflection of the composite beam.

The double integral of the curvature function $\kappa(x) = \frac{M(x)}{E\, I_y}$ determines the elastic deflection of a beam.

If a beam is subject to a uniformly distributed load the deflection equals to:

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{E I_y} \tag{11}$$

Composite beams do not have one common Young's Modulus E and neither do they have one common second moment of area I_y. Therefore, a suitable approach for composite beams is required. This thesis approaches two assumptions. The first assumption is a replacement of the composite section with a substitute section of monolithic steel. The second assumption is based on the derivations in chapter 8.4.2 of (Kozma, 2020). This assumption is divided into three different states: no shear connection, rigid shear connection and flexible (linear elastic) shear connection. All assumptions are about the determination of a common second moment of area $I_{y,\, eff.}$ which reflects the characteristics of the composite beam. Under this condition the elastic deflection of the composite beam is set equal to:

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{E_a I_{y,eff}} \tag{11.1}$$

3.7.1. Determination of second moment of area

As explained, a common second moment of area must be determined. In the following, both assumptions will be applied and afterwards used to determine the respective deflections.

Assumption 1: Replacement of composite section with a substitute section of monolithic steel

$$n = \frac{E_a}{E_t} = \frac{210000\, MPa}{8000\, MPa} = 26{,}25 \tag{12}$$

$$b = \frac{2500mm}{n} = \frac{2500mm}{26{,}25} = 95{,}24mm \tag{13}$$

	$I_{y,i}$ cm^4	A_i cm^2	z_i cm	$A{*}z_i$ cm^3	$(z_s\text{-}z_i)^2$ cm^2	$A_i(z_s\text{-}z_i)^2$ cm^4
t	2363,90	136,80	7,2	984,96	107,80	14747,56
a	23128,00	84,46	34,4	2905,42	282,81	23886,65
Σ	25491,90	221,26	-	3890,38	-	38634,21

Table 12: Calculations for the second moment of area

Determination of total center of gravity:

$$z_s = \frac{\Sigma A_i z_i}{\Sigma A_i} = \frac{3890{,}38\ cm^3}{221{,}26\ cm^2} = 17{,}58\ cm \tag{14}$$

Determination of second moment of area:

$$I_y = \Sigma I_{y,i} + \Sigma A_i (z_s - z_i)^2 = 25491{,}90\ cm^4 + 38634{,}21\ cm^4 = 64126{,}11\ cm^4 \tag{15}$$

<u>Assumption 2.1: No shear connection</u>

$$I_{y,eff} \approx I_{y,a} = 23128{,}00 cm^4 \tag{16}$$

<u>Assumption 2.2: Rigid shear connection</u>

$$I_{y,eff} = I_{y,a} + \frac{I_{y,t}}{n} + \frac{A_t A_a}{A_t + n A_a} \cdot a^2 \tag{17}$$

Where:

$$a = z_a - z_t = 34{,}4cm - 7{,}2cm = 27{,}20cm$$

$$n = 26{,}25$$

$$I_{y,eff} = 23128{,}00cm^4 + \frac{62208{,}00cm^4}{26{,}25} + \frac{3600cm^2 \cdot 84{,}46cm^2}{3600cm^2 + 26{,}25 \cdot 84{,}46cm^2} \cdot (27{,}20cm)^2$$

$$= 64168{,}94cm^4$$

<u>Assumption 2.3: Flexible (linear elastic) shear connection (Method EL1)</u>

$$I_{y,eff} = I_{y,a} + \frac{I_{y,t}}{n} + \frac{A_t/n}{1 + \frac{A_t}{nA_a} + \left(\frac{E_a}{k_{sc}/s_{sc,eq}}\right)\left(\frac{\pi}{L}\right)^2\left(\frac{A_t}{n}\right)} \cdot a^2 \tag{18}$$

Where:

$$a = z_a - z_t = 34{,}4cm - 7{,}2cm = 27{,}20cm$$

$$n = 26{,}25$$

$$L = 1000cm$$

$$k_{sc} = 0{,}7 P_{Rd,k}/s = 0{,}7 \cdot 50{,}52kN/0{,}25cm = 141{,}45kN/cm$$

$s_{sc,eq} = 33{,}75cm$ (longitudinal spacing distance in between connectors)

$$I_{y,eff} = 23128{,}00cm^4 + \frac{62208{,}00cm^4}{26{,}25} + \frac{3600cm^2/26{,}25}{1 + \frac{3600cm^2}{26{,}25 \cdot 84{,}46cm^2} + \left(\frac{21000kN/cm^2}{141{,}45/33{,}75cm}\right)\left(\frac{\pi}{1000cm}\right)^2\left(\frac{3600cm^2}{26{,}25}\right)} \cdot (27{,}20cm)^2$$

$$= 36285{,}14cm^4$$

3.7.2. Elastic deflection determination

The elastic deflection as shown previously depends on the characteristics of the section (i.e., the Young's Modulus and the second moment of area) as well as on the characteristics of the structural system (i.e., the span width (length) of the beam) and the loading applied on the structure.

The individual Young's Moduli are reduced to only the steel's Yong's Modulus:

$$E_a = 21000kN/cm^2$$

The second moment of area was determined according to the assumptions in the previous section.

The length of the beam (i.e., the span width) equals to:

$$l = 1000cm$$

The load combination for SLS integrity differs from the load combination used for ULS integrity. For SLS, the safety factors do not apply, but combination factors have to be used. The SLS adapted load combination for the analyzed system is determined by:

Load combination SLS	
e_k	$= g_{1,k} + 0{,}8 \cdot g_{2,k} + 0{,}4 \cdot q_k$
	$= 2{,}5kN/m + 0{,}8 \cdot 2{,}5kN/m + 0{,}4 \cdot 12{,}5kN/m$
	$= 9{,}5kN/m = 0{,}095kN/cm$

Table 13: Computation of load combination SLS

Given these values, the elastic deflection in regard to each assumption results as follows:

Assumption 1: Replacement of composite section with a substitute section of monolith steel

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095kN/cm \cdot (1000cm)^4}{21000kN/cm^2 \cdot 64126{,}11\ cm^4} = 0{,}92\ cm \quad (11.1)$$

Assumption 2.1: No shear connection

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095kN/cm \cdot (1000cm)^4}{21000kN/cm^2 \cdot 23128{,}00\ cm^4} = 2{,}55\ cm \quad (11.2)$$

Assumption 2.2: Rigid shear connection

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095kN/cm \cdot (1000cm)^4}{21000kN/cm^2 \cdot 64168{,}94\ cm^4} = 0{,}92\ cm \quad (11.3)$$

Assumption 2.3: Flexible (linear elastic) shear connection (Method EL1)

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095 kN/cm \cdot (1000cm)^4}{21000 kN/cm^2 \cdot \; 36285{,}14 cm^4} = \; 1{,}62 \; cm \tag{11.4}$$

The maximal defelection based on the given assumtions equals to 2,55cm.

The maximal allowed deflection equals to:

$$\delta_{max} = \frac{l}{300} = \frac{1000cm}{300} = 3{,}33cm \tag{19}$$

The SLS integrity is proofed by:

$$2{,}55cm \; < \; 3{,}33cm$$

The elastic deflection remains in an very acceptable range. The SLS integrety is therefore fulfilled for the analyzed system.

4. Structural Analysis of a beam based on experimental testing S460

For a second structural analysis the same cross section and same system are used. However, the steel grade gets increased. In knowledge that the result of the last structural analysis was already a too high performing cross section, the increase of the steel grade from S355 to S460 will worsen the degree of utilization. Instead of looking for a more suitable cross section for the given situation, the aim of this analysis is to approach the assumption that steel of grade S460 might be more compatible with the LVL timber as the points of plasticity align better for this combination.

4.1. System

The system remains the same as previously.

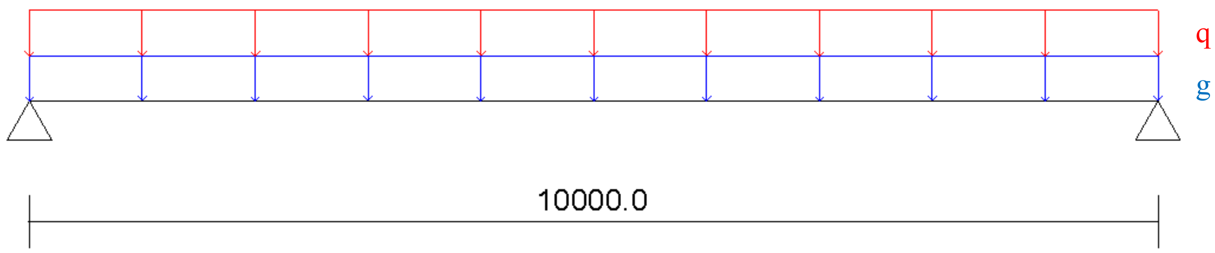


Figure 21: Analyzed system with loading distribution

4.2. Section and material properties

The section remains the same as previously, but the steel grade got increased to S460.

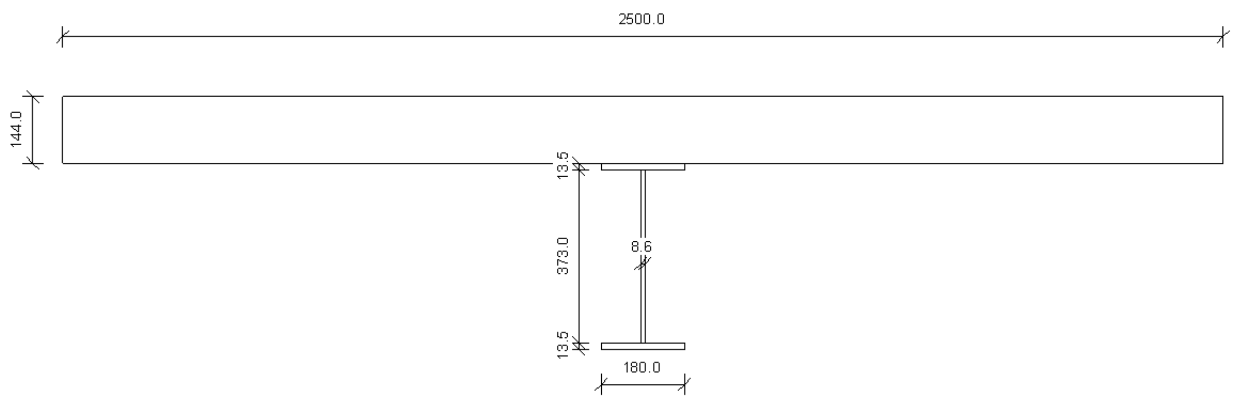


Figure 22: Section of analyzed system

The distribution of connectors remains unchanged.

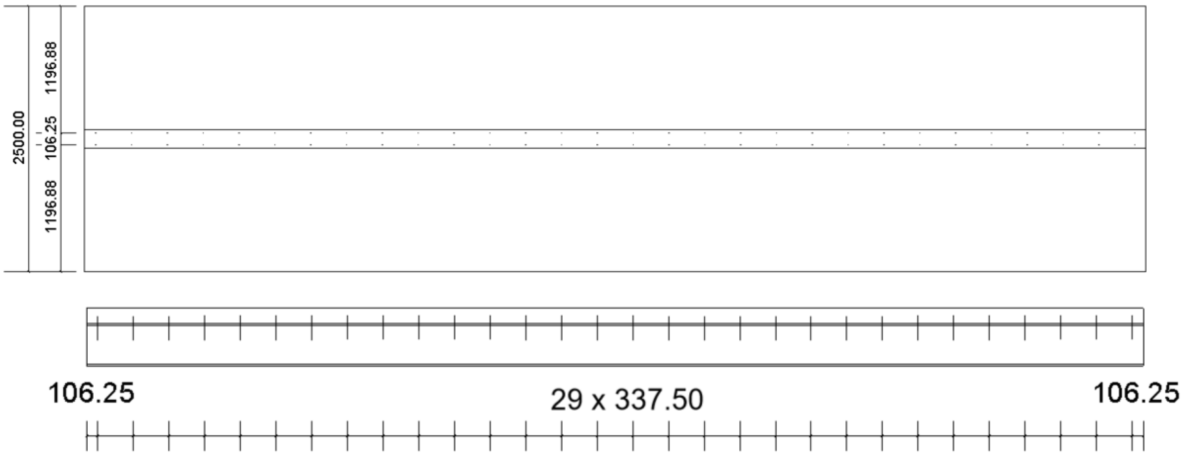


Figure 23: Distribution of connectors

The material properties of LVL Kerto Q remain unchanged.

But the material properties of steel change:

Steel of the steel grade S460 also has symmetrical behavior under compression and under tension but is higher performing:

Youngs's modulus	$E = 210000\ N/mm^2$
Design compression and tension strength	$f_{y,d} = \frac{f_y}{\gamma_M} = \frac{460\ N/mm^2}{1} = 460\ N/mm^2$
Yield strain	$\varepsilon_{y,d} = \frac{f_y}{E} = \frac{460\ N/mm^2}{210000\ N/mm^2} = 0{,}219\%$
Limiting multiplication factor	$k_{a,c} = k_{a,t} = 89$

Table 14: Material characteristics of steel S460

4.3. Loading

The loading remains the same as previously, given that the increased steel grade does not change the deadload of the IPE beam. The result of the previously explained load combination will be used.

$$e = 25{,}5kN$$

4.4. Reactions

As the loading remained the same, also the reactions of the system do not change.

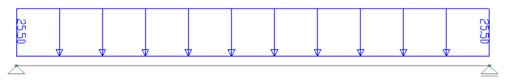
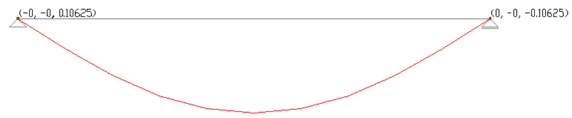
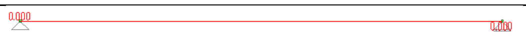
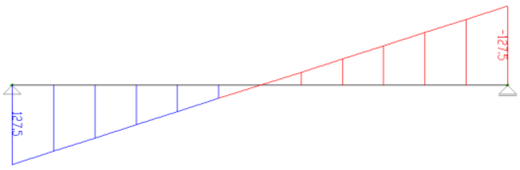
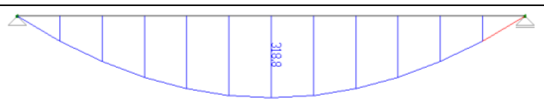
Geometry		
		
Deformation		
		
Horizontal forces		
N	= 0 kN	
Vertical forces		
A=B= $V_{z,\,max}$	= 25,5 kN/m · 10m / 2 = 127,5 kN	
Bending moment		
M_{max}	= 25,5 kN/m · 10m · 10m / 8 = 318,75 kNm	

Table 15: Reactions of the system

4.5. ULS integrity

The determination of ULS integrity follows the same process as shown in the previous chapter.

4.5.1. Stress strain controlled bending moment

A new computation in the MATLAB application will be launched. The only changed input is due to the increased steel grade:

$$f_y = 460MPa$$

The input for geometry, material properties and strain limits:

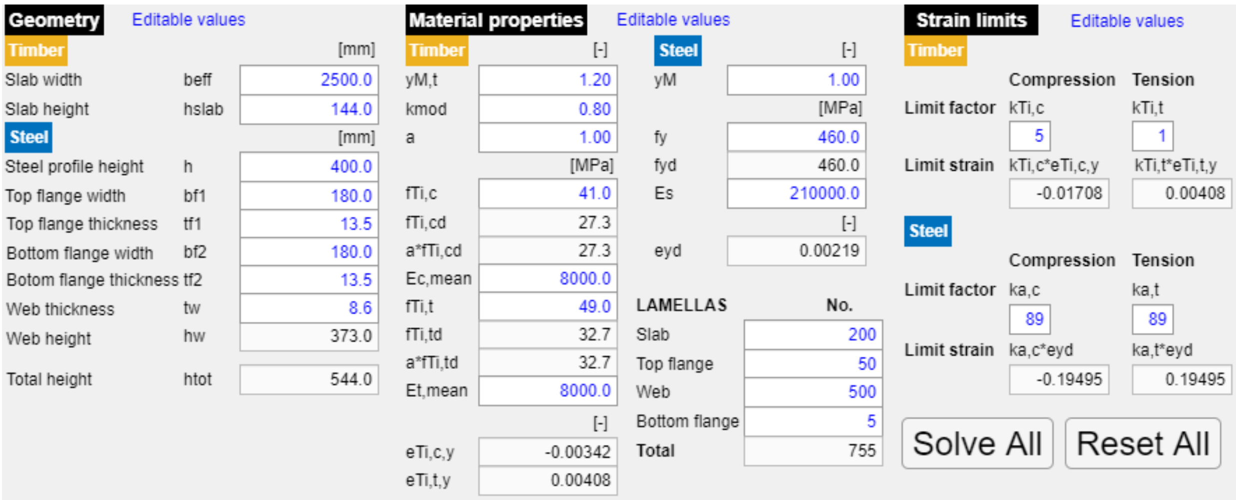


Figure 24: IPE400, S355, t=2500x144: geometry, material properties, strain limits

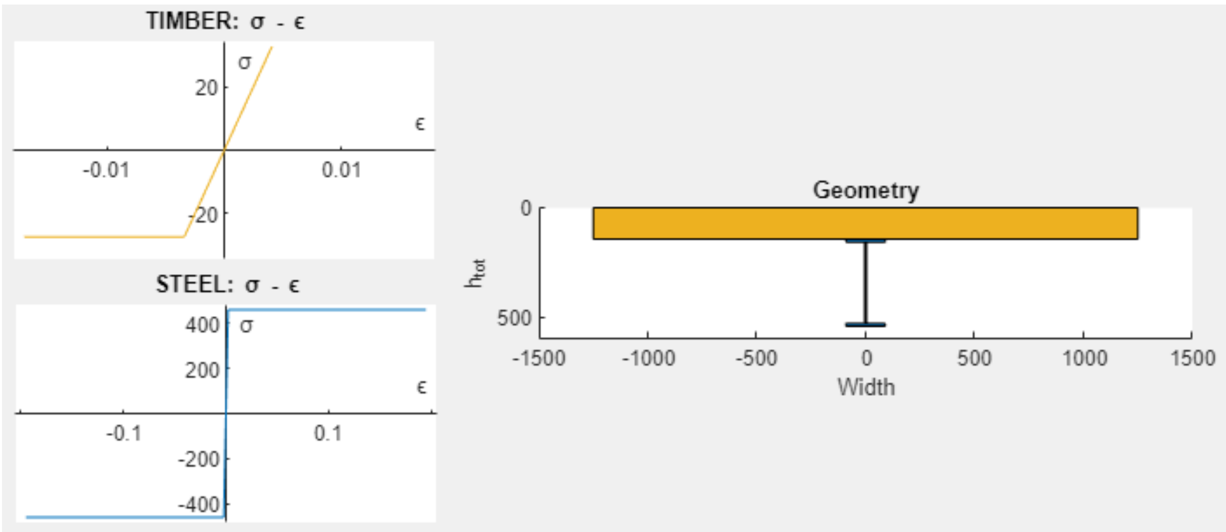


Figure 25: IPE400, S355, t=2500x144: stress-strain distribution, geometry illustration

Results for full shear connection:

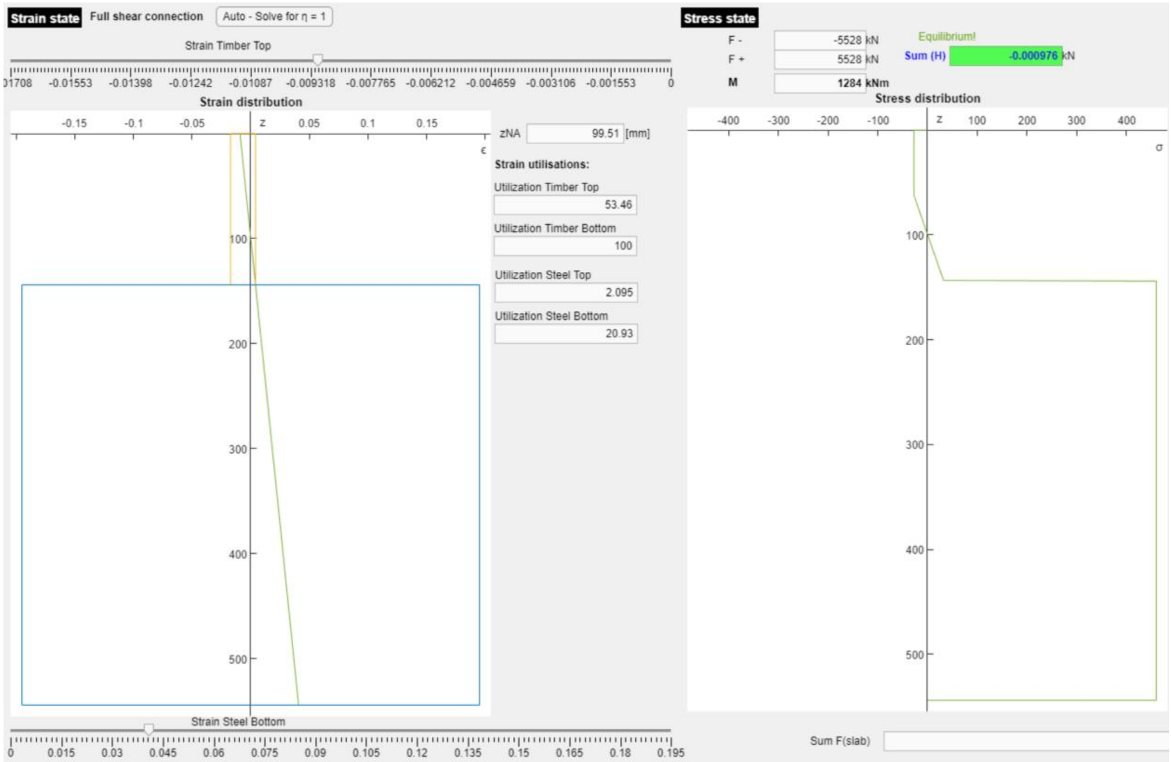


Figure 26: IPE400, S460, t=2500x144: Full shear connection - results

Results for no shear connection:

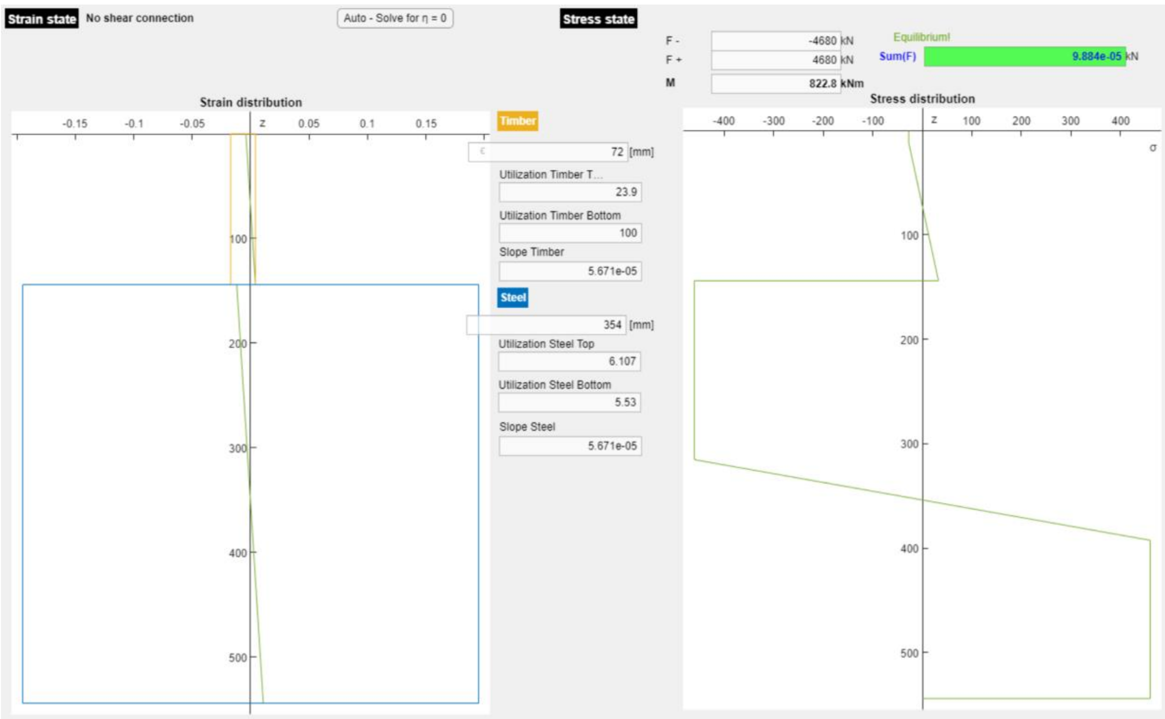


Figure 27: IPE400, S460, t=2500x144: No shear connection - results

Results for partial shear connection:

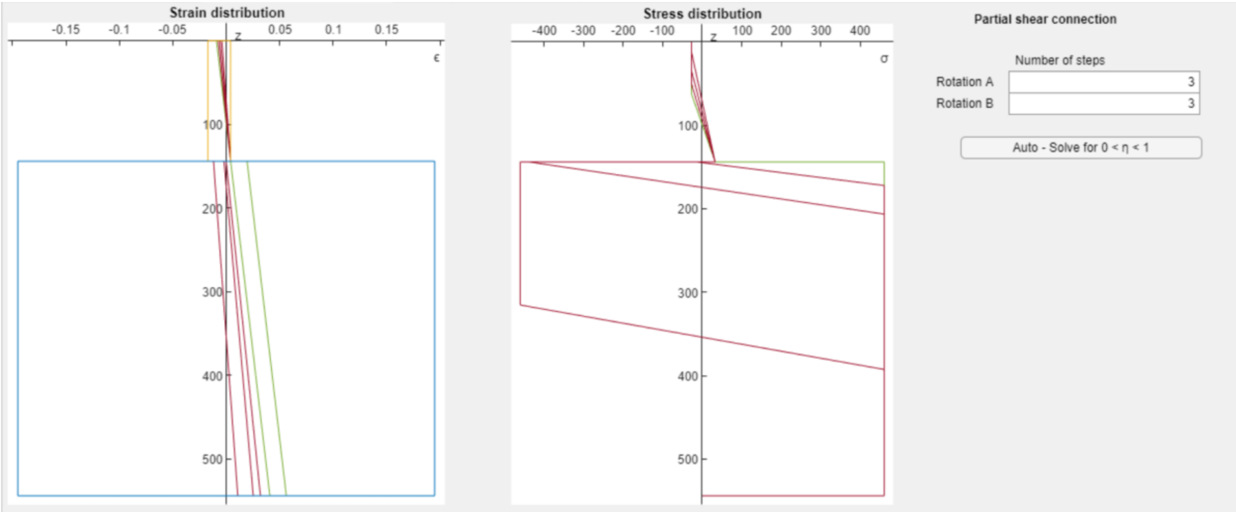


Figure 28: IPE400, S355, t=2500x144: Partial shear connection- computation steps

Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0091	0.0041	0.0041	0.0408	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
1	-0.0091	0.0041	0.0195	0.0562	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
2	-0.0091	0.0041	0.0195	0.0562	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
3	-0.0091	0.0041	0.0195	0.0562	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
4	-0.0074	0.0041	-7.3843e-05	0.0320	-2.8168e+03	2.8158e+03	-0.9996	0.7590	1.2257e+03
5	-0.0058	0.0041	-0.0021	0.0253	-1.6165e+03	1.6155e+03	-0.9994	0.4356	1.1330e+03
6	-0.0041	0.0041	-0.0119	0.0108	78.4320	-79.4300	-0.9980	-0.0211	822.4785

Figure 29: IPE400, S355, t=2500x144: Partial shear connection - table

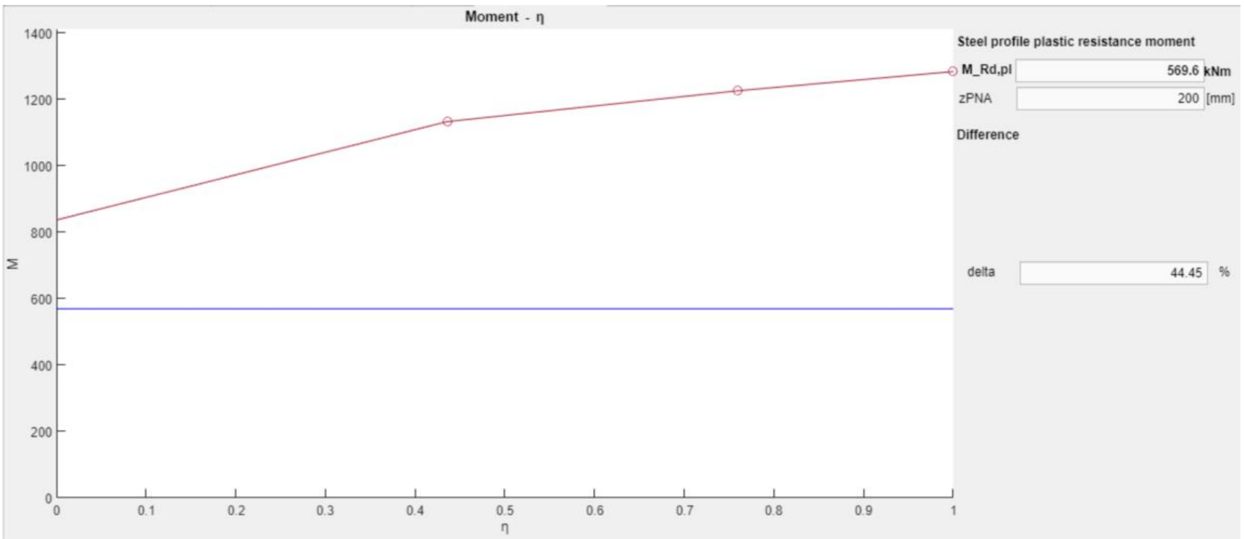


Figure 30: IPE400, S355, t=2500x144: Partial shear conection - M-eta-distribution

It shall be noted that a more detailed M-eta-distribution would have been better, however the MATLAB application could not compute more steps for this specific cross section with the given properties.

4.5.2. Effective shear resistance of connectors

The computations of the algorithm by Kozma remain unchanged after the increase of the steel grade. The effective shear resistance remains:

$$P_{Rd,eff} = k_{flex} \cdot P_{1,d} = 0{,}6789 \cdot 917{,}72kN = \mathbf{61{,}18kN} \tag{4.1}$$

4.5.3. Ultimate limit state integrity (ULS)

Given the new horizontal shear resistance of the full shear connection and the unchanged shear resistance of all connectors together the degree of shear connection is determined by:

$$\frac{N_c}{N_{c,f}} = \frac{1835{,}4kN}{5528kN} = 0{,}332 \tag{5.1}$$

$$\eta = 0{,}332$$

Then the applicable moment resistance is determined by linear interpolation:

$$M_{pl} = \frac{822{,}4 - 1133}{-0{,}0211 - 0{,}4356} \cdot (0{,}332 - 0{,}4356) + 1133 = 1062{,}6kNm \tag{6.1}$$

The ULS integrity is proofed by:

$$M_{Rd} = 1062{,}6kNm > 318{,}7kNm = M_{Ed} \tag{7.1}$$

Additionally, the degree of utilization is calculated:

$$\frac{M_{Ed}}{M_{Rd}} = \frac{318{,}7kNm}{1062{,}6kNm} = 0{,}300 \tag{8.1}$$

As stated at the beginning of this chapter, the utilization of this cross section is even worse than the previous one and therefore should not be used for execution of the given project situation.

4.6. Verification of results

The here given results shall also be verified by hand calculations. The previously explained process gets applied again.

1. Determination of a suitable lamella distribution

The same lamella distribution is chosen (5-5-10-5).

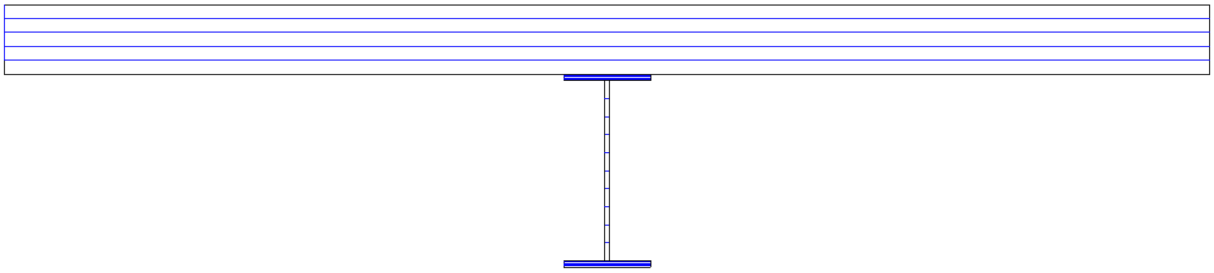


Figure 31: Lamella distribution of section

2. Determination of area and lever arm of each lamella

As the dimensions of the cross section remain the same, the areas A_i and lever arms z_i remain the same as well.

3. Assignation of ε-values

Based on the values obtained from the application, the ε-values for z =0 mm (timber), z=144 mm (timber and steel) and z = 544 mm (steel) are used to find the ε-values of each lamella. The determination is done by linear interpolation in between z = 0 mm and z = 144 mm (timber) for the first five lamellas and in between z = 144 mm (steel) and z = 544 mm for the remaining 20 lamellas due to the change of material. This differentiation is only important for the partial shear connection as its strain distribution is not continuous but composed of two separate parallel linear distributions.

4. Determination of applicable σ-values by using stress-strain-diagrams of the materials

Based on the stress-strain diagrams of each material the σ-values are determined.
The following new rules apply:

LVL Kerto Q	For $\varepsilon > 0{,}00408$	-
	For $0{,}00408 < \varepsilon < -0{,}00342$	$\sigma = E \cdot \varepsilon$
	For $\varepsilon > -0{,}00342$	$\sigma = -27{,}3 N/mm^2$
Steel S460	For $\varepsilon > 0{,}00219$	$\sigma = 460 N/mm^2$
	For $0{,}00219 < \varepsilon < -0{,}00219$	$\sigma = E \cdot \varepsilon$
	For $\varepsilon > -0{,}00219$	$\sigma = -460 N/mm^2$

Table 16: Determing rules of stress-strain distribution

5. Calculation of inner forces

The inner forces are obtained by the multiplication of stress times area.

6. Calculation of inner moments

The inner moments are obtained by the multiplication of inner forces times lever arms.

7. Summing up inner forces and moments

The sum of inner forces and the sum of inner moments shall be calculated. The sum of inner forces should be equal to 0 for an equilibrium.

8. Comparison with results obtained from application

For comparison, the sum of inner moments shall be divided by the previously obtained result of the application.

The results of both verifications are shown as tables. The final value for accuracy shows how close the manual computations got to the results of the application. A value equal to one would imply perfect agreement.

Full shear connection

	Lamella	A_i mm²	Z_i mm	ε -	σ N/mm²	F_i kN	M_i kNm
	-	-	0,00	-0,009136	-	-	-
timber	1,00	72000,00	14,40	-0,007814	-27,30	-1965,60	-28,30
	2,00	72000,00	43,20	-0,005171	-27,30	-1965,60	-84,91
	3,00	72000,00	72,00	-0,002528	-20,22	-1456,13	-104,84
	4,00	72000,00	100,80	0,000115	0,92	66,36	6,69
	5,00	72000,00	129,60	0,002758	22,07	1588,84	205,91
	-	-	144,00	0,004080	-	-	-
	-	-	144,00	0,004084	-	-	-
steel flange	6,00	486,00	145,35	0,004267	460,00	223,56	32,49
	7,00	486,00	148,05	0,004633	460,00	223,56	33,10
	8,00	486,00	150,75	0,005000	460,00	223,56	33,70
	9,00	486,00	153,45	0,005366	460,00	223,56	34,31
	10,00	486,00	156,15	0,005732	460,00	223,56	34,91
steel web	11,00	320,78	176,15	0,008446	460,00	147,56	25,99
	12,00	320,78	213,45	0,013506	460,00	147,56	31,50
	13,00	320,78	250,75	0,018566	460,00	147,56	37,00
	14,00	320,78	288,05	0,023626	460,00	147,56	42,50
	15,00	320,78	325,35	0,028686	460,00	147,56	48,01
	16,00	320,78	362,65	0,033747	460,00	147,56	53,51
	17,00	320,78	399,95	0,038807	460,00	147,56	59,02
	18,00	320,78	437,25	0,043867	460,00	147,56	64,52
	19,00	320,78	474,25	0,048887	460,00	147,56	69,98
	20,00	320,78	511,85	0,053987	460,00	147,56	75,53
steel flange	21,00	486,00	531,85	0,056701	460,00	223,56	118,90
	22,00	486,00	534,55	0,057067	460,00	223,56	119,50
	23,00	486,00	537,25	0,057433	460,00	223,56	120,11
	24,00	486,00	539,95	0,057800	460,00	223,56	120,71
	25,00	486,00	542,65	0,058166	460,00	223,56	121,31
	-	-	544,00	0,058349	-	-	-
				Sums:	Manual	-20,95	1284,00
					Application	0	1284,00
						Accuracy:	1,00000

Table 17: Computation results for verification of full shear connection

<u>Exemplary partial shear connection with η= 0,4356</u>

	Lamella	A_i mm²	Z_i mm	ε -	σ N/mm²	F_i kN	M_i kNm
	-	-	0,00	-0,005800	-	-	-
timber	1,00	72000,00	14,40	-0,004810	-27,30	-1965,60	-28,30
	2,00	72000,00	43,20	-0,002830	-22,64	-1630,08	-70,42
	3,00	72000,00	72,00	-0,000850	-6,80	-489,60	-35,25
	4,00	72000,00	100,80	0,001130	9,04	650,88	65,61
	5,00	72000,00	129,60	0,003110	24,88	1791,36	232,16
	-	-	144,00	0,004100	-	-	-
	-	-	144,00	-0,002100	-	-	-
steel flange	6,00	486,00	145,35	-0,002008	-421,58	-204,89	-29,78
	7,00	486,00	148,05	-0,001823	-382,74	-186,01	-27,54
	8,00	486,00	150,75	-0,001638	-343,90	-167,14	-25,20
	9,00	486,00	153,45	-0,001453	-305,06	-148,26	-22,75
	10,00	486,00	156,15	-0,001268	-266,22	-129,38	-20,20
steel web	11,00	320,78	176,15	0,000102	21,48	6,89	1,21
	12,00	320,78	213,45	0,002657	460,00	147,56	31,50
	13,00	320,78	250,75	0,005212	460,00	147,56	37,00
	14,00	320,78	288,05	0,007767	460,00	147,56	42,50
	15,00	320,78	325,35	0,010322	460,00	147,56	48,01
	16,00	320,78	362,65	0,012878	460,00	147,56	53,51
	17,00	320,78	399,95	0,015433	460,00	147,56	59,02
	18,00	320,78	437,25	0,017988	460,00	147,56	64,52
	19,00	320,78	474,25	0,020522	460,00	147,56	69,98
	20,00	320,78	511,85	0,023098	460,00	147,56	75,53
steel flange	21,00	486,00	531,85	0,024468	460,00	223,56	118,90
	22,00	486,00	534,55	0,024653	460,00	223,56	119,50
	23,00	486,00	537,25	0,024838	460,00	223,56	120,11
	24,00	486,00	539,95	0,025023	460,00	223,56	120,71
	25,00	486,00	542,65	0,025208	460,00	223,56	121,31
	-	-	544,00	0,025300	-	-	-
				Sums:	Manual	-26,00	1121,64
					Application	0,00	1133,00
						Accuracy:	0,9900

Table 18: Computation results for verification of partial shear connection η= 0,4356

Both verification computations show satisfactory results. The application's computations seem trustworthy.

4.7. Serviceability limite state integrity (SLS)

As shown in the previous chapter, the deflection depends only on the Young's modulus, the second moment of area and the span width of the beam. As all these properties are independent of f_y, so changing the steel grade alone has no impact on the behavior of deflection. The previously determined second moments of area and deflections remain the same and therefore will not be repeated. The results for the elastic deformation are however shown for completion.

4.7.1. Elastic deflection determination

Assumption 1: Replacement of composite section with a substitute section of monolith steel

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095kN/cm \cdot (1000cm)^4}{21000kN/cm^2 \cdot\ 64126{,}11\ cm^4} = 0{,}92\ cm \tag{11.5}$$

Assumption 2.1: No shear connection

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095kN/cm \cdot (1000cm)^4}{21000kN/cm^2 \cdot\ 23128{,}00\ cm^4} = \ 2{,}55\ cm \tag{11.6}$$

Assumption 2.2: Rigid shear connection

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095kN/cm \cdot (1000cm)^4}{21000kN/cm^2 \cdot\ 64168{,}94\ cm^4} = \ 0{,}92\ cm \tag{11.7}$$

Assumption 2.3: Flexible (linear elastic) shear connection (Method EL1)

$$\delta = \frac{5}{384} \cdot \frac{e_k l^4}{EI_y} = \frac{5}{384} \cdot \frac{0{,}095kN/cm \cdot (1000cm)^4}{21000kN/cm^2 \cdot\ 36285{,}14cm^4} = \ 1{,}62\ cm \tag{11.8}$$

The maximal defelection based on the given assumtions equals to 2,55cm.

The maximal allowed deflection equals to:

$$\delta_{max} = \frac{l}{300} = \frac{1000cm}{300} = 3{,}33cm \tag{19.1}$$

The SLS integrity is proofed by:

$$2{,}55cm\ <\ 3{,}33cm$$

The elastic deflection remains in an very acceptable range. The SLS integrety is therefore fulfilled for the analyzed system.

5. Parameter study

5.1. Process description

The aim of the parameter study is to find a more suitable section for the given situation as well as to discover any relations between the parameters and the outcomes.

The here provided parameter study focuses on different IPE steel sections of steel grades S355 and S460 composited with LVL Kerto Q slabs of varying width and height. The ULS process described in Figure 32 was repeated for each combination.

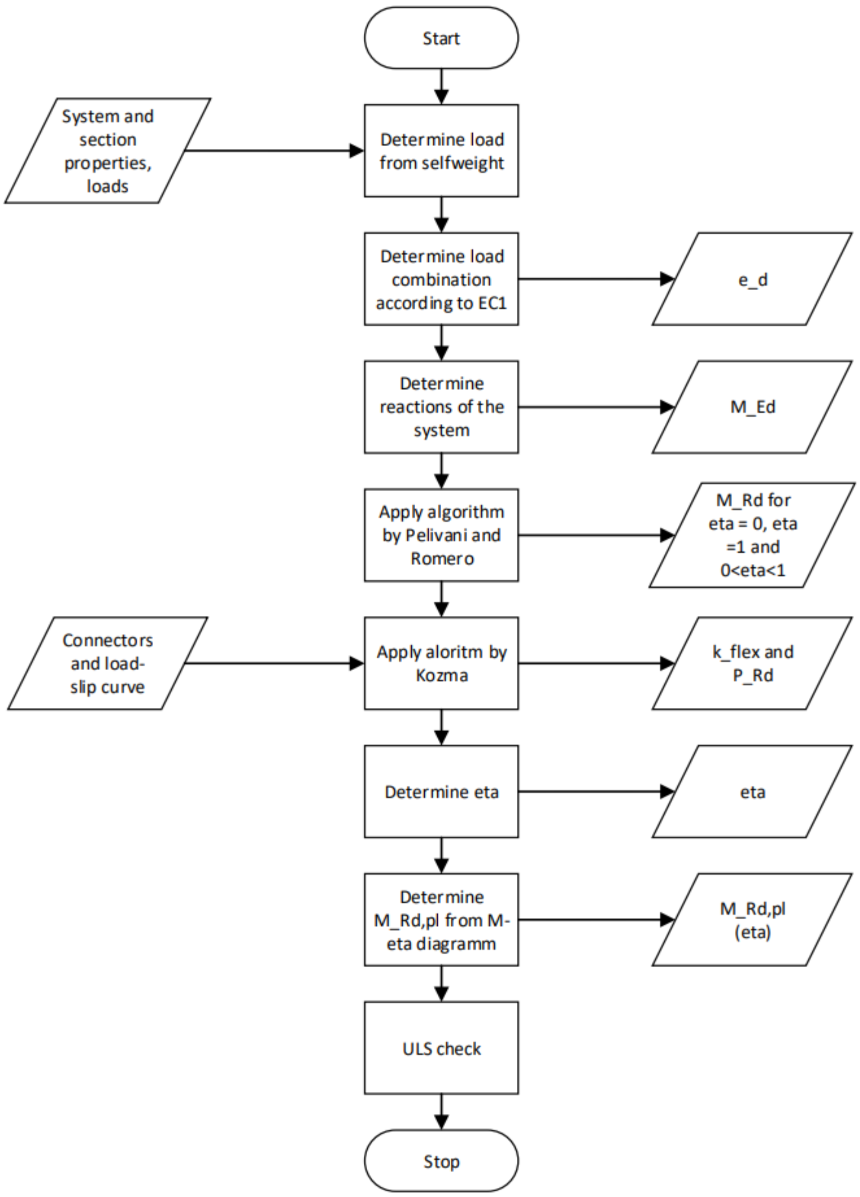


Figure 32: Process description of ULS integrity check

5.2. Presentation of results

				IPE 400								IPE300							
				S355															
				2500x144		1666x144		2500x75		1666x75		2500x144		1666x144		2500x75		1666x75	
Load	Dead load	g1,k	kN	2,5		2,5		1,6		1,6		2,3		2,3		1,4		1,4	
		g2,k	kN	2,5		2,5		2,5		2,5		2,5		2,5		2,5		2,5	
	Payload	qk	kN	12,5		12,5		12,5		12,5		12,5		12,5		12,5		12,5	
	Load combination	ed	kN	25,5		25,5		24,3		24,3		25,2		25,2		24,0		24,0	
Reactions		Ved	kN	127,5		127,5		121,6		121,6		125,9		125,9		119,9		119,9	
		MEd	kNm	318,7		318,7		303,9		303,9		314,7		314,7		299,8		299,8	
Romero/Pelivani	Full shear connection	F	kN	4932,0		3959,0		3534,0		2879,0		4213,0		3240,0		2815,0		2308,0	
		M	kNm	1065,0		954,0		742,3		697,3		700,4		600,1		420,5		387,8	
		timber top	-	44,070		61,650		85,330		100,000		35,380		43,100		51,310		80,680	
		timber bottom	-	100,000		100,000		100,000		28,350		100,000		100,000		100,000		100,000	
		steel top	-	2,714		2,714		2,714		0,769		2,714		2,714		2,714		2,714	
		steel bottom	-	24,150		29,700		68,860		65,430		16,740		18,560		36,880		50,220	
	No shear connection	F	kN	4287,0		3320,0		2919,0		2415,0		3784,0		2816,0		2412,0		1908,0	
		M	kNm	693,8		608,8		504,6		482,9		471,9		385,6		280,8		258,4	
		timber top	-	23,900		23,900		23,900		23,900		23,900		23,900		23,900		23,900	
		timber bottom	-	100,000		100,000		100,000		100,000		100,000		100,000		100,000		100,000	
		steel top	-	8,023		7,862		14,960		14,800		6,241		6,045		11,440		11,250	
		steel bottom	-	7,055		7,216		13,990		14,150		5,068		5,263		10,270		10,470	
	Partial shear connection	M-eta distribution		Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M
				1,0000	1065,0	1,0000	954,0	1,0000	742,2	1,0000	697,2	1,0000	700,4	1,0000	600,0	1,0000	420,5	1,0000	387,8
				1,0000	1065,0	1,0000	954,0	1,0000	742,2	0,9199	694,4	1,0000	700,4	1,0000	600,0	1,0000	420,5	1,0000	387,8
				1,0000	1065,0	1,0000	954,0	1,0000	742,2	0,8309	690,6	1,0000	700,4	1,0000	600,0	1,0000	420,5	1,0000	387,8
				1,0000	1065,0	1,0000	954,0	1,0000	742,2	0,7344	685,9	1,0000	700,4	1,0000	600,0	1,0000	420,5	1,0000	387,8
				0,7327	1010,0	0,7776	916,0	0,8179	728,4	0,6141	676,3	0,7004	656,7	0,7296	564,4	0,7535	404,3	0,8112	378,4
				0,3995	931,6	0,4626	851,0	0,5266	698,6	0,4103	655,4	0,3565	601,3	0,3954	514,2	0,4279	379,0	0,5153	359,2
				-0,0274	693,4	-0,0182	608,0	-0,0143	504,9	-0,0096	483,1	-0,0426	471,5	-0,0284	385,3	-0,0222	281,0	-0,0148	258,6
Kozma		PRd,eff	kN	61,2		61,2		61,2		61,2		61,2		61,2		61,2		61,2	
		Nc	kN	1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4	
ULS		eta	-	0,372		0,464		0,519		0,638		0,436		0,566		0,652		0,795	
		Mpl	kNm	916,3		851,2		697,9		678,2		614,1		539,9		396,4		377,4	
		MEd/Mpl	-	0,348		0,374		0,435		0,448		0,512		0,583		0,756		0,795	

Table 19: Resullts of parameter study: S355 – IPE 400, IPE 300

				IPE240								IPE180							
				S355															
				2500x144		1666x144		2500x75		1666x75		2500x144		1666x144		2500x75		1666x75	
Load	Dead load	g1,k	kN	2,1		2,1		1,3		1,3		2,1		2,1		1,1		1,1	
		g2,k	kN	2,5		2,5		2,5		2,5		2,5		2,5		2,5		2,5	
	Payload	qk	kN	12,5		12,5		12,5		12,5		12,5		12,5		12,5		12,5	
	Load combination	ed	kN	25,0		25,0		23,8		23,8		24,9		24,9		23,7		23,7	
Reactions		Ved	kN	125,1		125,1		119,2		119,2		124,6		124,6		118,3		118,3	
		MEd	kNm	312,7		312,7		297,9		297,9		311,6		311,6		295,9		295,9	
Romero/Pelivani	Full shear connection	F	kN	3846,0		2872,0		2448,0		1941,0		3498,0		2524,0		2100,0		1593,0	
		M	kNm	544,3		447,6		286,2		257,2		421,6		327,3		184,3		157,6	
		timber top	-	31,750		36,430		41,000		54,640		28,700		31,220		33,530		39,640	
		timber bottom	-	100,000		100,000		100,000		100,000		100,000		100,000		100,000		100,000	
		steel top	-	2,714		2,714		2,714		2,714		2,714		2,714		2,714		2,714	
		steel bottom	-	13,250		14,130		26,300		31,250		10,180		10,540		18,370		20,030	
	No shear connection	F	kN	3528,0		2560,0		2154,0		1650,0		3285,0		2318,0		1909,0		1405,0	
		M	kNm	383,3		296,4		191,1		168,3		319,9		232,2		126,6		103,4	
		timber top	-	23,900		23,900		23,900		23,900		23,900		23,900		23,900		23,900	
		timber bottom	-	100,000		100,000		100,000		100,000		100,000		100,000		100,000		100,000	
		steel top	-	5,195		4,971		9,357		9,132		4,178		3,916		7,299		7,037	
		steel bottom	-	3,852		4,076		8,013		8,237		2,607		2,869		5,728		5,990	
	Partial shear connection	M-eta distribution		Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M
				1,0000	544,2	1,0000	447,5	1,0000	286,2	1,0000	257,2	1,0000	421,5	1,0000	327,2	1,0000	184,3	1,0000	157,6
				1,0000	544,2	1,0000	447,5	1,0000	286,2	1,0000	257,2	1,0000	421,5	1,0000	327,2	1,0000	184,3	1,0000	157,6
				1,0000	544,2	1,0000	447,5	1,0000	286,2	1,0000	257,2	1,0000	421,5	1,0000	327,2	1,0000	184,3	1,0000	157,6
				1,0000	544,2	1,0000	447,5	1,0000	286,2	1,0000	257,2	1,0000	421,5	1,0000	327,2	1,0000	184,3	1,0000	157,6
				0,6817	509,3	0,7050	417,3	0,7225	271,6	0,7619	246,4	0,6579	397,1	0,6784	305,1	0,6916	173,2	0,7176	148,2
				0,3304	467,4	0,3626	378,3	0,3859	251,5	0,4397	229,1	0,2936	369,0	0,3256	278,7	0,3444	159,6	0,3794	135,7
				-0,0594	383,0	-0,0396	296,0	-0,0309	190,9	-0,0206	168,1	-0,0950	319,6	-0,0633	231,9	-0,0495	126,4	-0,0330	103,2
Kozma		PRd,eff	kN	61,2		61,2		61,2		61,2		61,2		61,2		61,2		61,2	
		Nc	kN	1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4	
ULS		eta	-	0,477		0,639		0,750		0,946		0,525		0,727		0,874		1,152	
		Mpl	kNm	484,9		409,8		273,0		254,7		386,8		308,5		179,8		157,6	
		MEd/Mpl	-	0,645		0,763		1,091		1,169		0,805		1,010		1,646		1,877	

Table 20: Resullts of parameter study: S355 – IPE 240, IPE 180

				IPE 400								IPE300							
				S460															
				2500x144		1666x144		2500x75		1666x75		2500x144		1666x144		2500x75		1666x75	
Load	Dead load	g1,k	kN	2,5		2,5		1,6		1,6		2,3		2,3		1,4		1,4	
		g2,k	kN	2,5		2,5		2,5		2,5		2,5		2,5		2,5		2,5	
	Payload	qk	kN	12,5		12,5		12,5		12,5		12,5		12,5		12,5		12,5	
	Load combina	ed	kN	25,5		25,5		24,3		24,3		25,2		25,2		24,0		24,0	
Reactions		Ved	kN	127,5		127,5		121,6		121,6		125,9		125,9		119,9		119,9	
		MEd	kNm	318,7		318,7		303,9		303,9		314,7		314,7		299,8		299,8	
Romero/Pelivani	Full shear connection	F	kN	5528,0		4555,0		3985,0		3156,0		4596,0		3623,0		3198,0		2613,0	
		M	kNm	1284,0		1160,0		923,5		866,9		819,5		714,1		516,8		477,8	
		timber top	-	53,460		87,110		100,000		100,000		39,710		51,850		66,280		100,000	
		timberbottom	-	100,000		100,000		65,830		2,326		100,000		100,000		100,000		73,850	
		steel top	-	2,095		2,095		1,379		0,204		2,095		2,095		2,095		1,547	
		steel bottom	-	20,930		29,120		55,470		45,440		13,710		15,920		33,700		42,780	
	No shear connection	F	kN	4680,0		3712,0		3327,0		2823,0		4031,0		3063,0		2671,0		2167,0	
		M	kNm	822,8		737,8		634,4		612,6		534,4		448,1		343,8		321,4	
		timber top	-	23,900		23,900		23,900		23,900		23,900		23,900		23,900		23,900	
		timberbottom	-	100,000		100,000		100,000		100,000		100,000		100,000		100,000		100,000	
		steel top	-	6,107		6,010		11,460		11,360		4,713		4,596		8,727		8,611	
		steel bottom	-	5,530		5,626		10,880		10,980		4,014		4,131		8,029		8,145	
	Partial shear connection	M-eta distribution		Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M
				1,0000	1283,8	1,0000	1603,0	1,0000	923,5	1,0000	866,8	1,0000	819,5	1,0000	714,0	1,0000	516,8	1,0000	477,8
				1,0000	1283,8	1,0000	1603,0	0,9499	921,1	0,9087	862,8	1,0000	819,5	1,0000	714,0	1,0000	516,8	0,9593	476,6
				1,0000	1283,8	1,0000	1603,0	0,8978	918,0	0,7952	857,0	1,0000	819,5	1,0000	714,0	1,0000	516,8	0,9175	475,1
				1,0000	1283,8	0,6948	1101,0	0,8439	914,6	0,6642	849,4	1,0000	819,5	0,6046	649,8	1,0000	516,8	0,8745	473,3
				0,7590	1225,7	-0,0141	737,4	0,7056	900,7	0,5554	839,2	0,7179	769,0	-0,0219	447,7	0,7869	501,0	0,7313	464,6
				0,4356	1133,0	Computation		0,4715	871,0	0,3711	810,9	0,3798	700,1	Computation		0,4766	472,6	0,4887	445,9
				-0,0211	822,4	3 -3 failed		-0,0110	634,6	-0,0087	612,9	-0,0329	534,0	3 -3 failed		-0,0171	0,0	-0,0114	321,1
Kozma		PRd,eff	kN	61,2		61,2		61,2		61,2		61,2		61,2		61,2		61,2	
		Nc	kN	1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4	
ULS		eta	-	0,332		0,403		0,461		0,582		0,399		0,507		0,574		0,702	
		Mpl	kNm	1062,6		951,3		869,6		841,7		704,1		618,2		481,5		462,4	
		MEd/Mpl	-	0,300		0,335		0,349		0,361		0,447		0,509		0,623		0,648	

Table 21: Resullts of parameter study: S460 – IPE 400, IPE 300

				IPE240								IPE180							
				S460															
				2500x144		1666x144		2500x75		1666x75		2500x144		1666x144		2500x75		1666x75	
Load	Dead load	g1,k	kN	2,1		2,1		1,3		1,3		2,1		2,1		1,1		1,1	
		g2,k	kN	2,5		2,5		2,5		2,5		2,5		2,5		2,5		2,5	
	Payload	qk	kN	12,5		12,5		12,5		12,5		12,5		12,5		12,5		12,5	
	Load combina	ed	kN	25,0		25,0		23,8		23,8		24,9		24,9		23,7		23,7	
Reactions		Ved	kN	125,1		125,1		119,2		119,2		124,6		124,6		118,3		118,3	
		MEd	kNm	312,7		312,7		297,9		297,9		311,6		311,6		295,9		295,9	
Romero/Pelivani	Full shear connection	F	kN	4120,0		3147,0		2723,0		2216,0		3669,0		2696,0		2272,0		1765,0	
		M	kNm	620,0		520,7		345,6		313,9		462,9		367,5		215,4		187,6	
		timber top	-	34,420		41,290		48,420		72,630		30,160		33,680		36,990		46,260	
		timberbottom	-	100,000		100,000		100,000		100,000		100,000		100,000		100,000		100,000	
		steel top	-	2,095		2,095		2,095		2,095		2,095		2,095		2,095		2,095	
		steel bottom	-	10,610		11,620		22,380		29,160		8,016		8,401		14,900		16,850	
	No shear connection	F	kN	3701,0		2733,0		2337,0		1833,0		3388,0		2421,0		2021,0		1517,0	
		M	kNm	419,0		332,0		227,3		204,5		336,3		248,6		143,4		120,2	
		timber top	-	23,900		23,900		23,900		23,900		23,900		23,900		23,900		23,900	
		timberbottom	-	100,000		100,000		100,000		100,000		100,000		100,000		100,000		100,000	
		steel top	-	3,891		3,757		7,103		6,969		3,086		2,930		5,495		5,339	
		steel bottom	-	3,091		3,224		6,302		6,436		2,150		2,306		4,559		4,715	
	Partial shear connection	M-eta distribution		Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M	Eta	M
				1,0000	620,0	1,0000	520,7	1,0000	345,6	1,0000	313,9	1,0000	462,8	1,0000	367,5	1,0000	215,3	1,0000	187,6
				1,0000	620,0	1,0000	520,7	1,0000	345,6	1,0000	313,9	1,0000	462,8	1,0000	367,5	1,0000	215,3	1,0000	187,6
				1,0000	620,0	1,0000	520,7	1,0000	345,6	1,0000	313,9	1,0000	462,8	1,0000	367,5	1,0000	215,3	1,0000	187,6
				1,0000	620,0	0,5640	464,1	1,0000	345,6	1,0000	313,9	1,0000	462,8	1,0000	367,5	1,0000	215,3	1,0000	187,6
				0,6960	578,2	-0,0306	331,7	0,7457	329,6	0,7984	303,8	0,6710	432,9	0,6923	340,9	0,7073	202,3	0,7394	177,2
				0,3504	525,2	Computation		0,4171	305,5	0,4945	284,9	0,3144	397,9	0,3454	307,3	0,3658	185,3	0,4086	162,0
				-0,0459	418,7	3 -3 failed		-0,0239	227,1	-0,0159	204,2	-0,0733	336,0	-0,0489	248,3	-0,0382	143,2	-0,0255	120,0
Kozma		PRd,eff	kN	61,2		61,2		61,2		61,2		61,2		61,2		61,2		61,2	
		Nc	kN	1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4		1835,4	
ULS		eta	-	0,445		0,583		0,674		0,828		0,500		0,681		0,808		1,040	
		Mpl	kNm	539,8		466,6		325,1		305,3		416,1		339,8		206,8		187,6	
		MEd/Mpl	-	0,579		0,670		0,916		0,976		0,749		0,917		1,431		1,577	

Table 22: Resullts of parameter study: S460 – IPE 240, IPE 180

For better visibility of the results and for the ease of comparison the following diagrams were created:

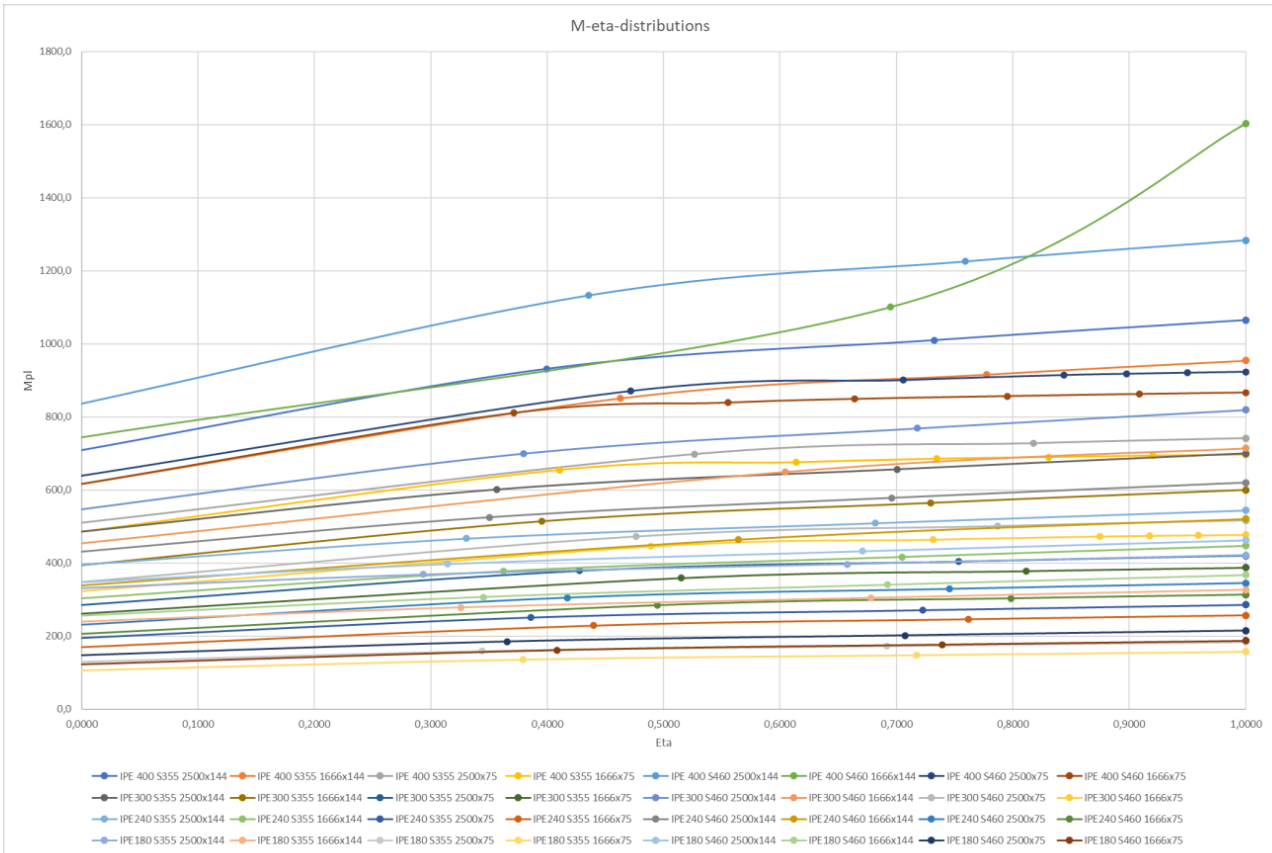


Figure 33: M-eta-distribution of all cross sections

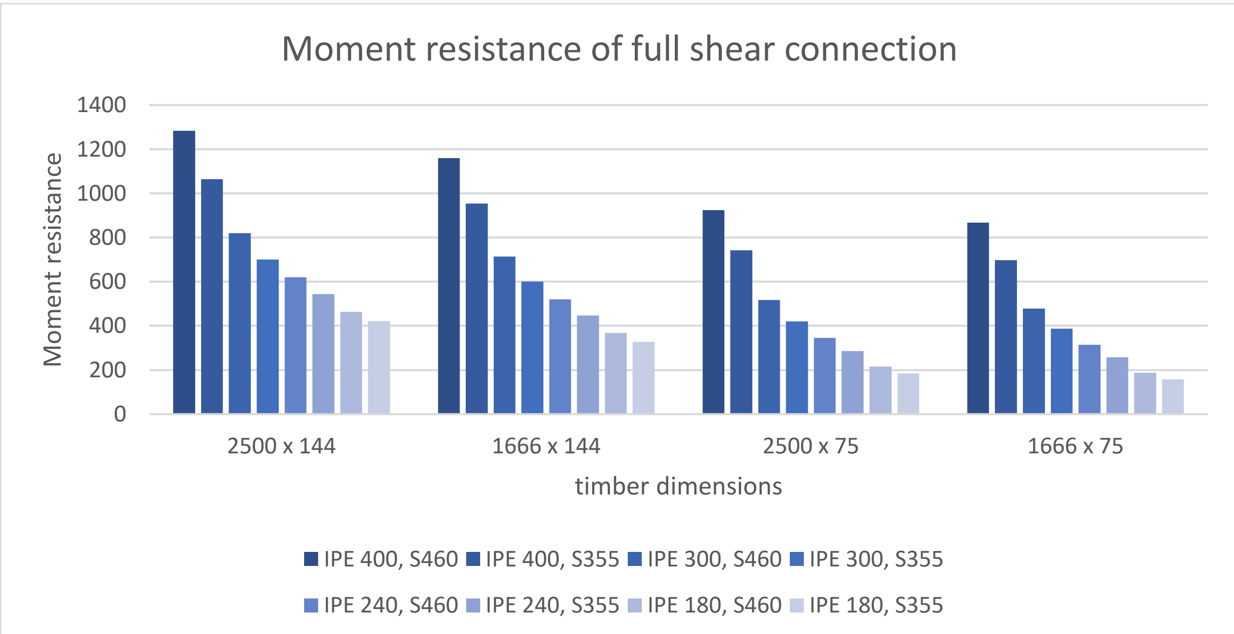


Figure 34: Moment resistance of full shear connection

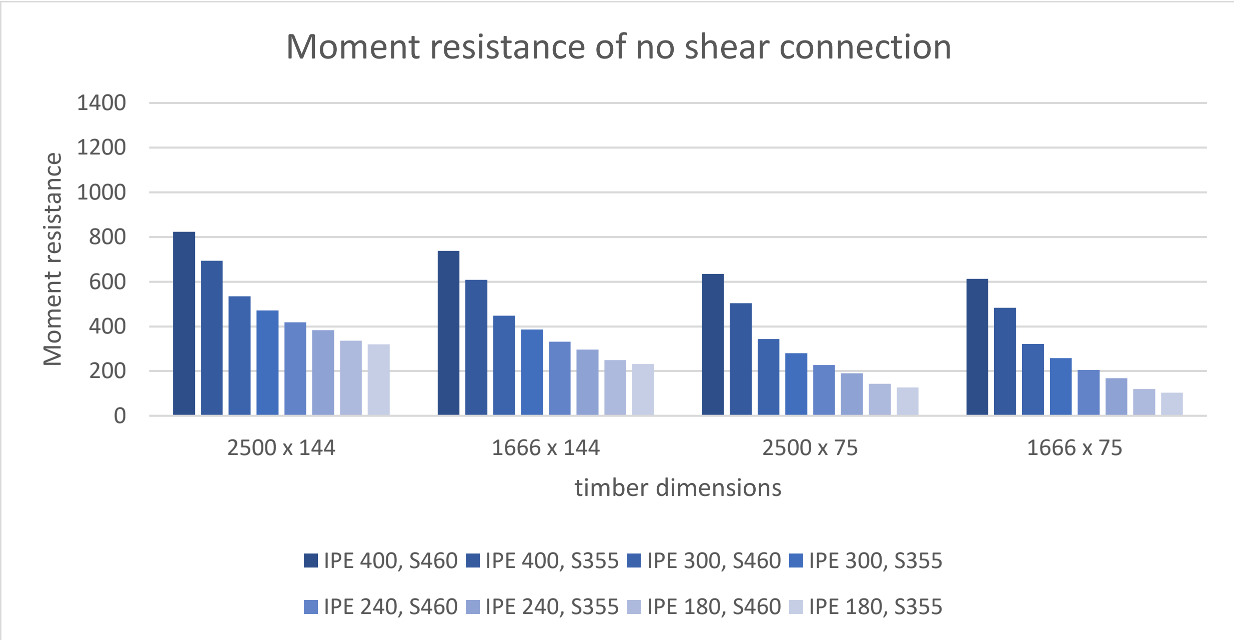


Figure 35: Moment resistance of no shear connection

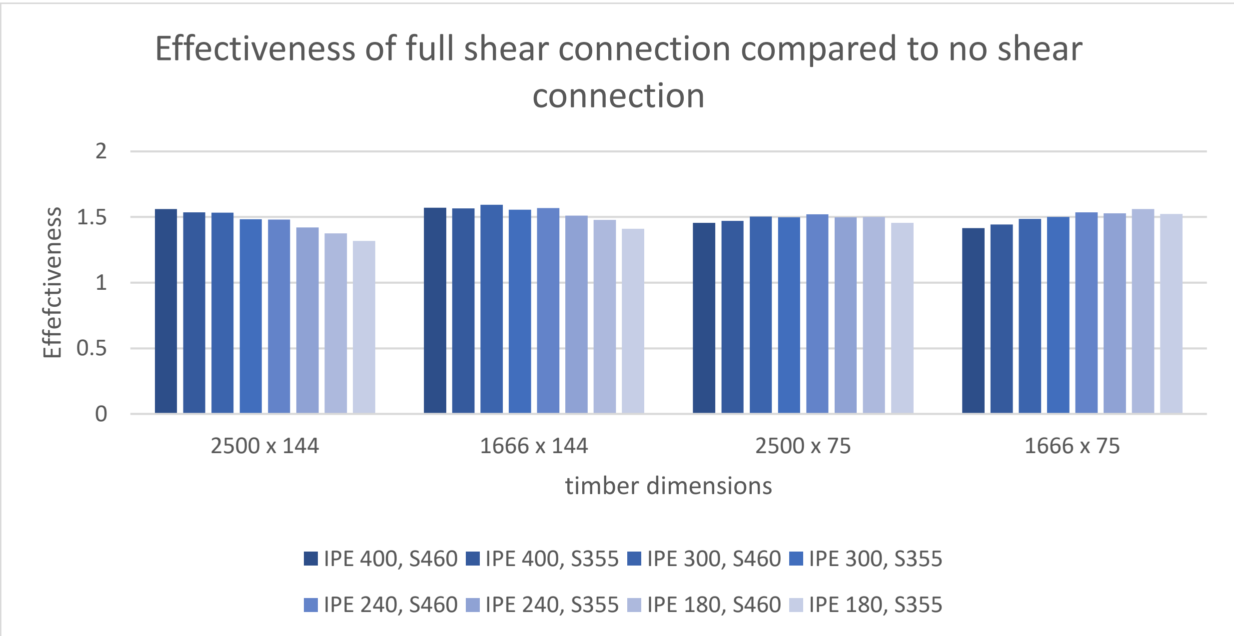


Figure 36: Effectiveness of full shear connection compared to no shear connection

Further diagrams such as an overlay of strain or stress distributions, an overview of the moment resistance in relation to the moment resistance of the steel profile or the timber profile, as well as an overview of the relation in between the deadload (or the total area) of the structure and the achievable moment resistance would been interesting to investigate. However, these will not be included in this thesis due to time limitations.

5.3. Discussion on results and assumed correlations

In total 32 different cross sections were analyzed following the process description shown in Figure 32. Four IPE cross sections (IPE 400, IPE 300, IPE 240, IPE 180) were chosen and each analyzed in combination with four different types of timber slabs (2500x144, 1666x144, 2500x75, 1666x75). All sixteen combinations were once analyzed for S355 and once for S460.

This discussion will focus on two main aspects. First, a more suitable solution for the in the previous chapters described system shall be chosen. Secondly, the agglomeration of results shall be used to identify irregularities, possible correlations, and other interesting remarks. The verification of made assumptions will not be included in this thesis but might be further investigated in future research. Hence, this thesis focuses on the discovery of assumptions only.

5.3.1. Identification of a more suitable solution for the given system

The quotient $\frac{M_{Ed}}{M_{pl}}$ is used to identify the most suitable solution based on the results of the parameter study. The quotient for each cross section can be found at the end of the previously shown tables. They are color coded according to the following rules:

Blue	Fulfills ULS, but economically bad
Green	Fulfills ULS and economically acceptable
Red	Does not fulfill ULS, therefore not applicable

Table 23: Color coding explanation

Based on the color coding, seven cross sections would be acceptable. For economic reasons the highest value would indicate the best solution. For this specific case, the IPE 240, S460 in combination with a timber LVL slab of 1666x75 would be the most suitable solution. However, before finally deciding, other requirements must be verified first. The SLS calculations must be repeated for the new cross section and checked for integrity. Further, the connection type and its dimensions should get verified for suitability.

5.3.2. Irregularities, possible correlations and other remarks based on the results

Interesting to note is the behavior of the MATLAB application in certain cases. While the application plots a moment-eta distribution with four values of η=1 for most cross sections, four cross sections were given a more detailed moment-eta distribution. All sections with a more detailed moment-eta distribution had a usage of 100% at the top of the timber slab for full shear connection, while all other cross sections had the 100% usage at the bottom of the timber slab. All these four cross sections had a timber slab thickness of 75mm. A correlation might be assumed and could be subject of further investigation.

Further, in three cases the MATLAB application failed the A:3 steps and B:3 steps computation for partial shear connection. An A:2 steps and B:2 steps computation, however, was possible. All three cases included cross sections where S460 steel and the dimensions 1666x144 for the LVL-timber slab were applied. Even though one other cross section of the same properties was computable, the persistence of the same error might be interesting for further investigation.

The moment-eta diagram in Figure 33 shows an overall well aligned distribution of the different cross sections but one exception is very noticeable. The IPE 400, S460, 1666x144 shows irregular distributions. The reason for this should be investigated.

The absolute values of the moment resistance in both cases, full shear connection (refer to Figure 34) and no shear connection (refer to Figure 35), do not imply any irregularities.

The effectiveness of full shear connection compared to no shear connection however shows different results depending on the timber dimensions. While the effectiveness decreases with decreasing steel profiles for bigger timber dimensions, the opposite is shown for the smallest timber dimension investigated. Further comparisons might lead to more detailed conclusions.

In general, most irregularities were found in connection with S460 steel profiles. This should be subject of further investigation to clarify whether technical or theoretical problems are the reason or whether the steel grade S460 is not very suitable for steel-timber composite structures.

6. Conclusion

While the construction industry is currently facing challenging urges for change towards a more sustainable approach, steel-timber composite structures might be one of the solutions. If the steel production reaches net zero or at least very small emissions as it is planned for example by Arcelor Mittal, steel-timber composite structures have great potential to be one of the main construction methods of the future. A low carbon footprint as well as the ability to disassemble the structures at the end-of-life for reuse in new constructions, both are great characteristics needed for the coming changes.

However, challenges such as the naturally grown timber with its wide range of mechanical characteristics, or the yet insufficiently investigated composite behavior of timber-steel composite structures reveal the demand for ongoing research. Some calculation methods and approaches already presented must get verified and further calculation methods and approaches might be adapted from other composite structures, such as the well-used steel-concrete composite structures.

The in this thesis explained approaches for the ultimate limit state and serviceability limit state integrity seem reasonable as also the verification calculations showed very satisfactory results. However, this theoretical approach should be verified with the real behavior. Large scale testing should be conducted, so that the real behavior can be compared to the computation results. The upcoming large-scale test at the University of Luxembourg offers this opportunity.

Especially the results given by the MATLAB application would be interesting to verify, as irregularities occur within the results. On a theoretical level the algorithms of the application, mainly for partial shear connection should be subject of further research as most computation problems occur when increasing the number of steps or a higher steel grade was used.

The algorithm used to transfer load-slip curves into an effective shear resistance were developed for Eurocode 4 structures, its suitability for timber-steel composite structures should therefore get verified. The same applies to the SLS integrity. The approaches used were developed for concrete-steel composite structures, it should be verified whether the same rules apply for timber-steel composite structures.

Summarily, timber-steel composite structures have great potential as one of the main future construction methods and therefore currently great potential for ongoing research.

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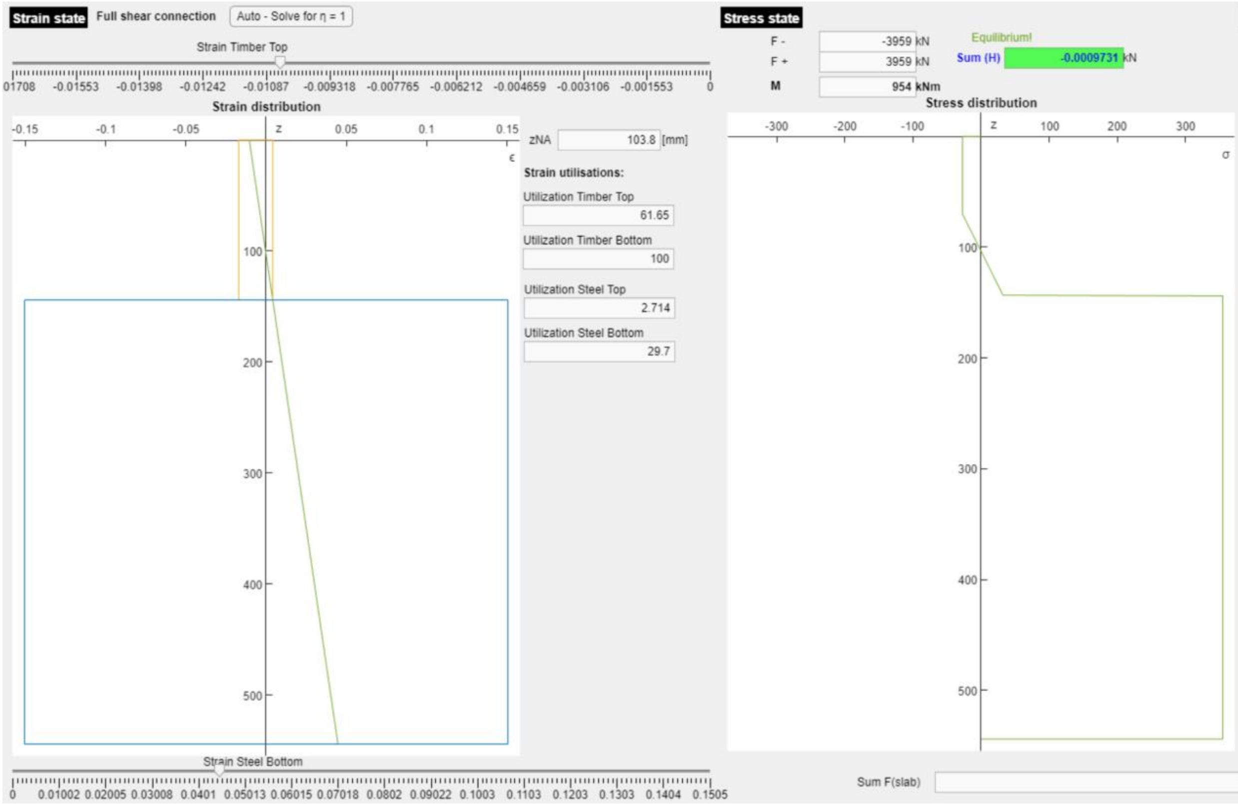
Annex A

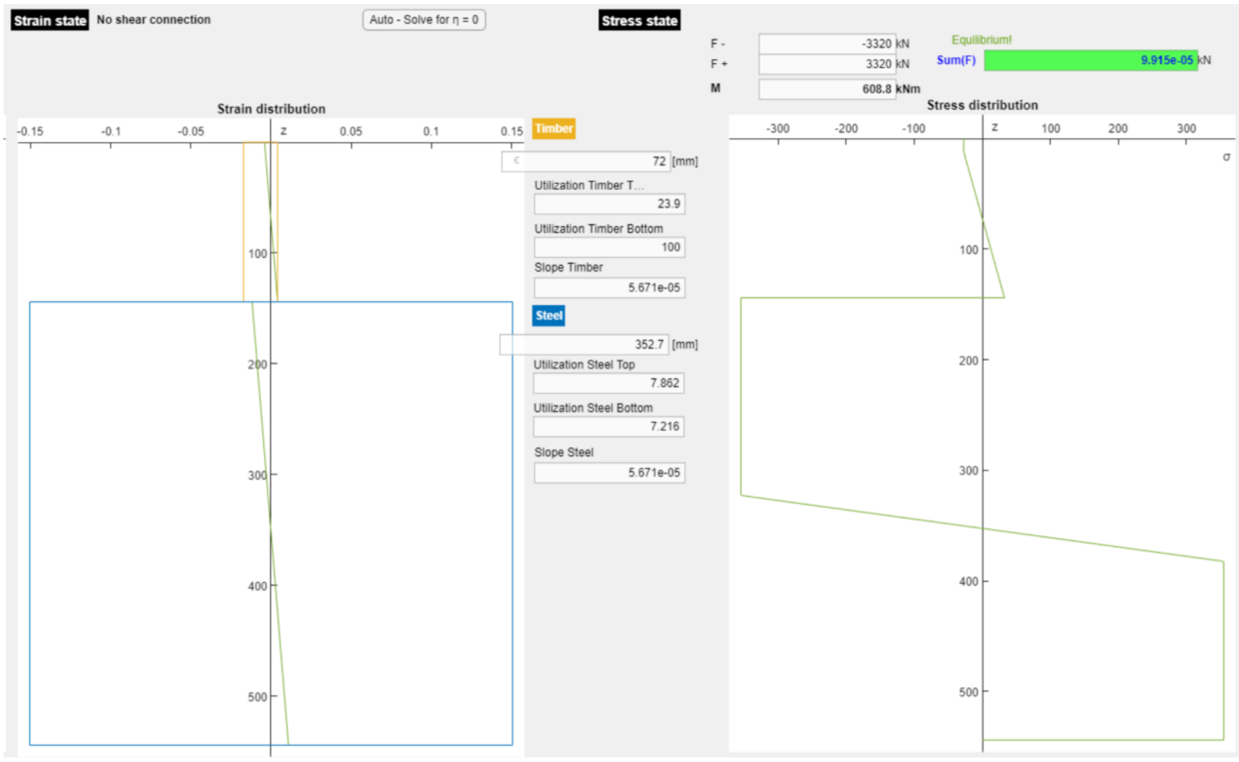
This annex contains all computation results obtained from the computations with the MATLAB application. They are included for future reference.

IPE 400, S355, t=1666x144

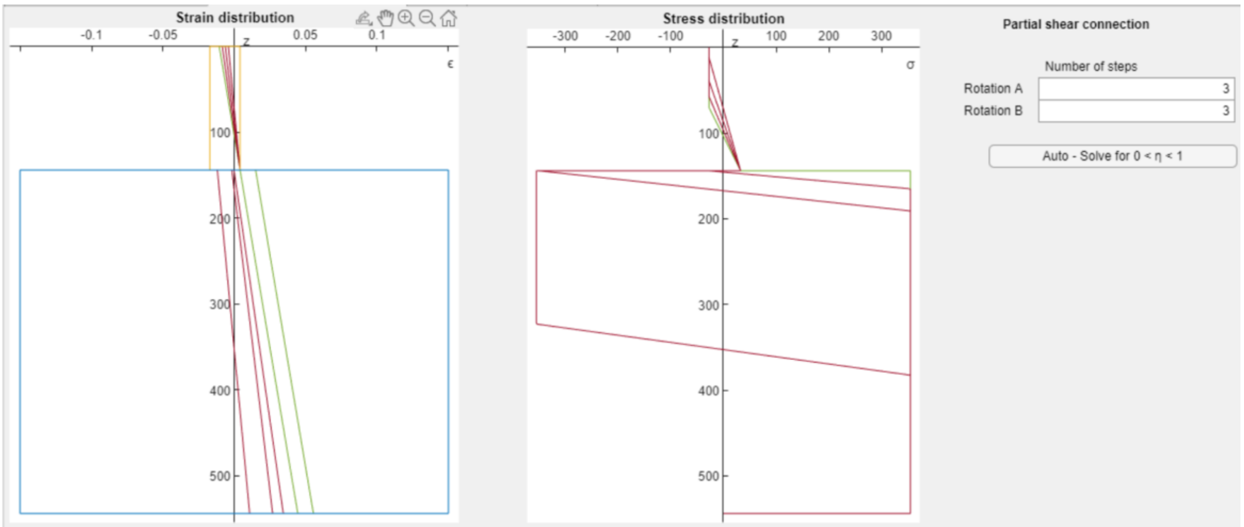
Results for full shear connection:



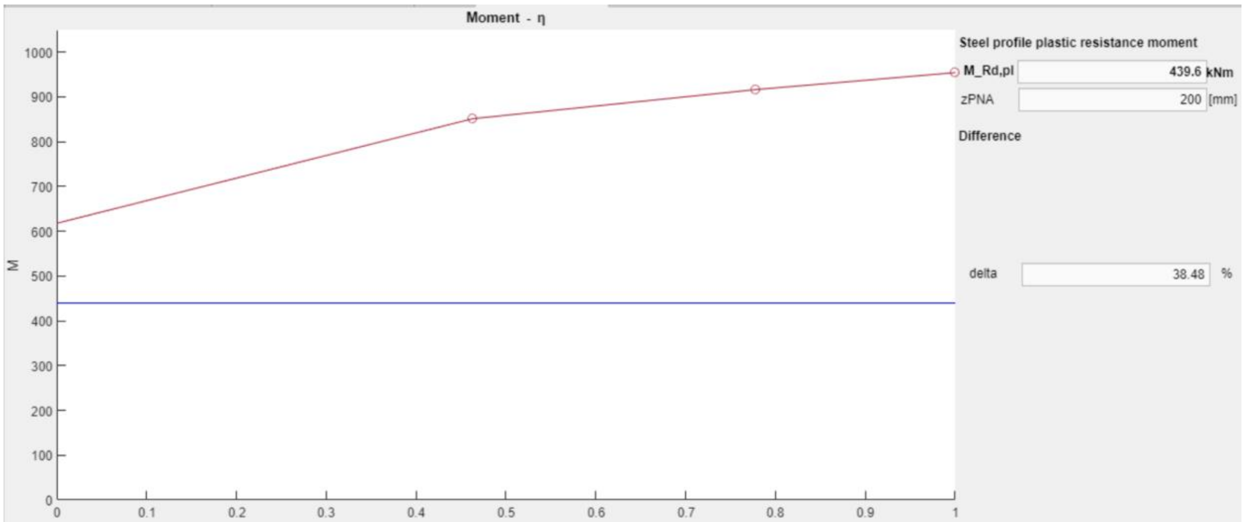
Results for no shear connection:



Results for partial shear connection:

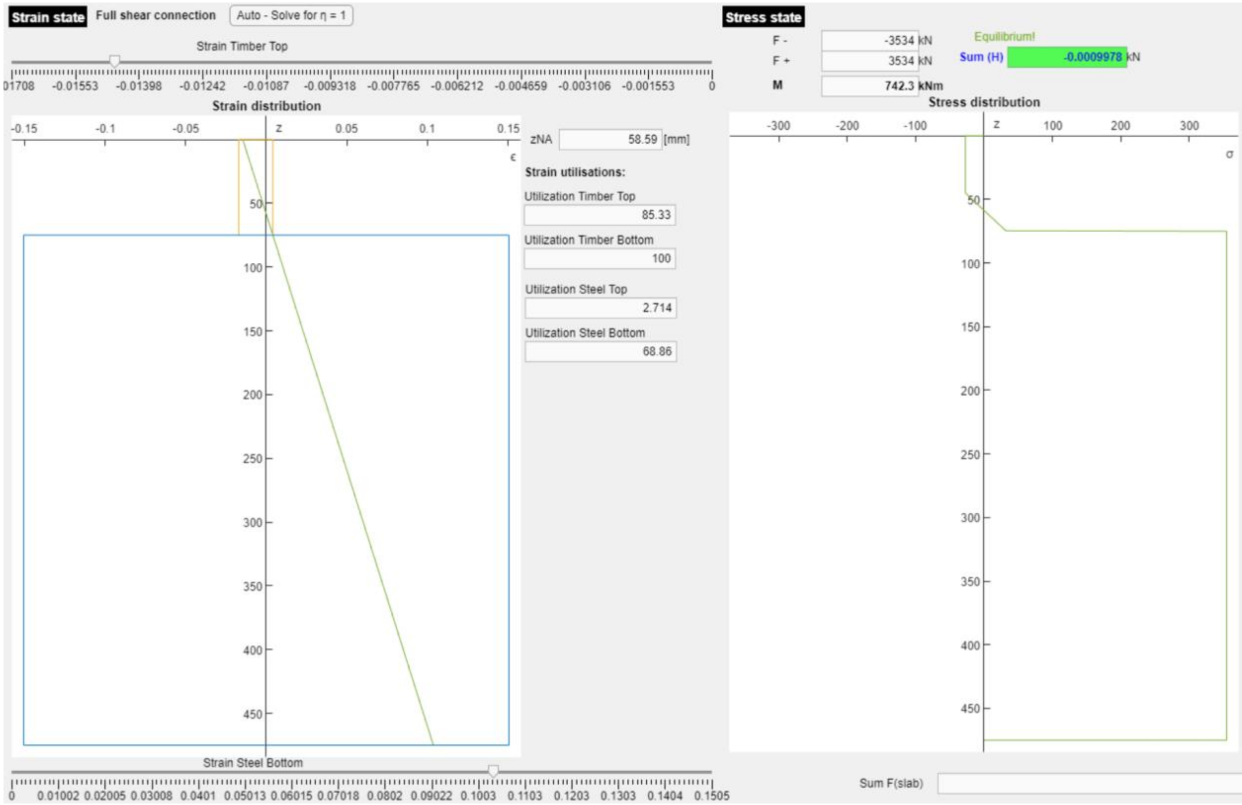


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0105	0.0041	0.0041	0.0447	-2.8641e+03	2.8641e+03	-9.7305e-04	1	953.9649
1	-0.0105	0.0041	0.0150	0.0556	-2.8641e+03	2.8641e+03	-9.7305e-04	1	953.9649
2	-0.0105	0.0041	0.0150	0.0556	-2.8641e+03	2.8641e+03	-9.7305e-04	1	953.9649
3	-0.0105	0.0041	0.0150	0.0556	-2.8641e+03	2.8641e+03	-9.7305e-04	1	953.9649
4	-0.0084	0.0041	-1.3497e-04	0.0345	-2.2272e+03	2.2262e+03	-0.9997	0.7776	916.0661
5	-0.0062	0.0041	-0.0017	0.0270	-1.3250e+03	1.3240e+03	-0.9919	0.4626	851.0698
6	-0.0041	0.0041	-0.0118	0.0108	52.2671	-53.2540	-0.9869	-0.0182	608.4332

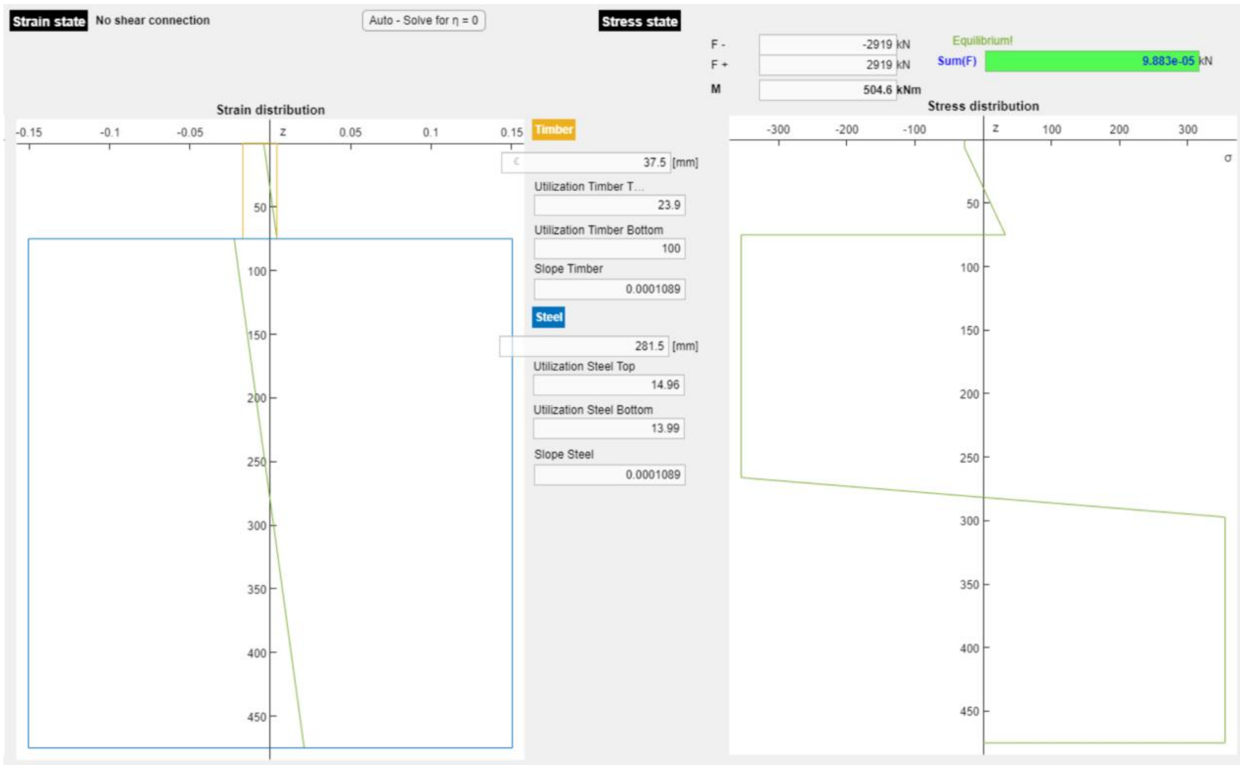


IPE 400, S355, t=2500x75

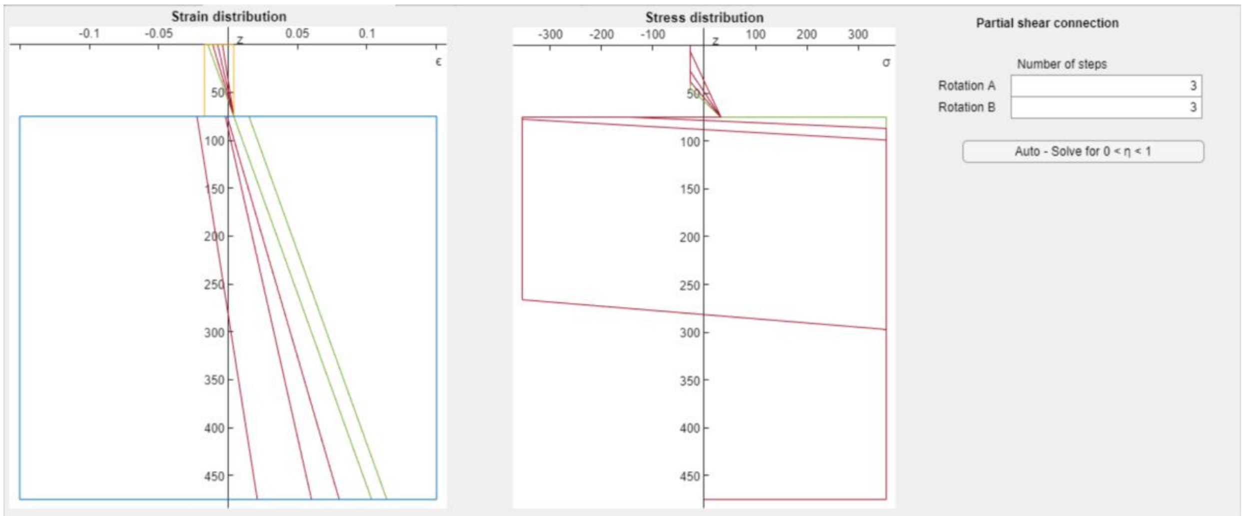
<u>Results for full shear connection:</u>



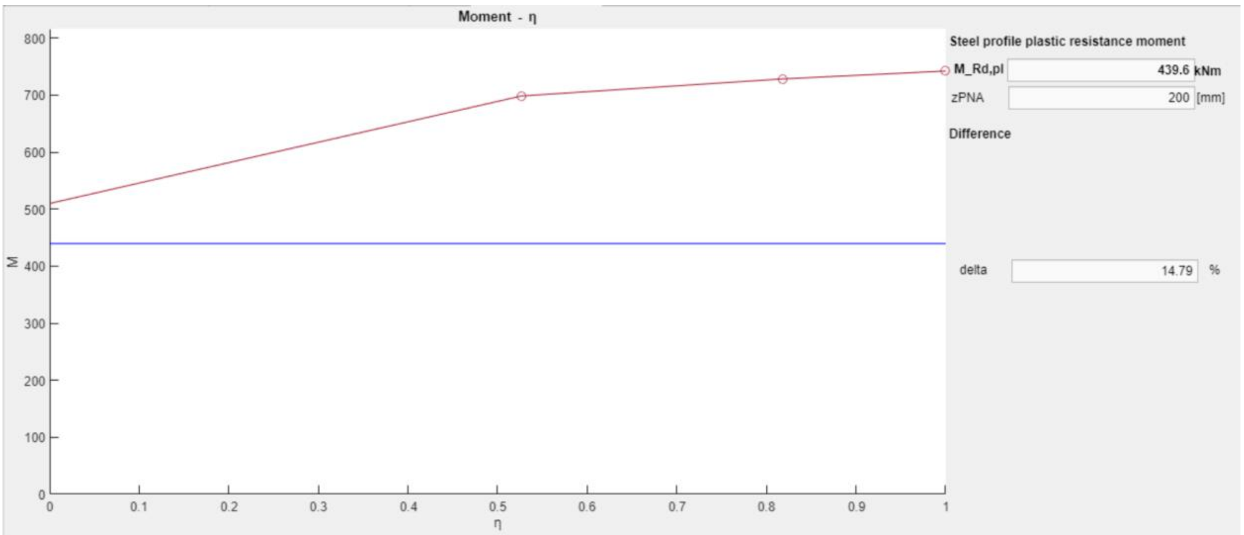
<u>Results for no shear connection:</u>



Results for partial shear connection:

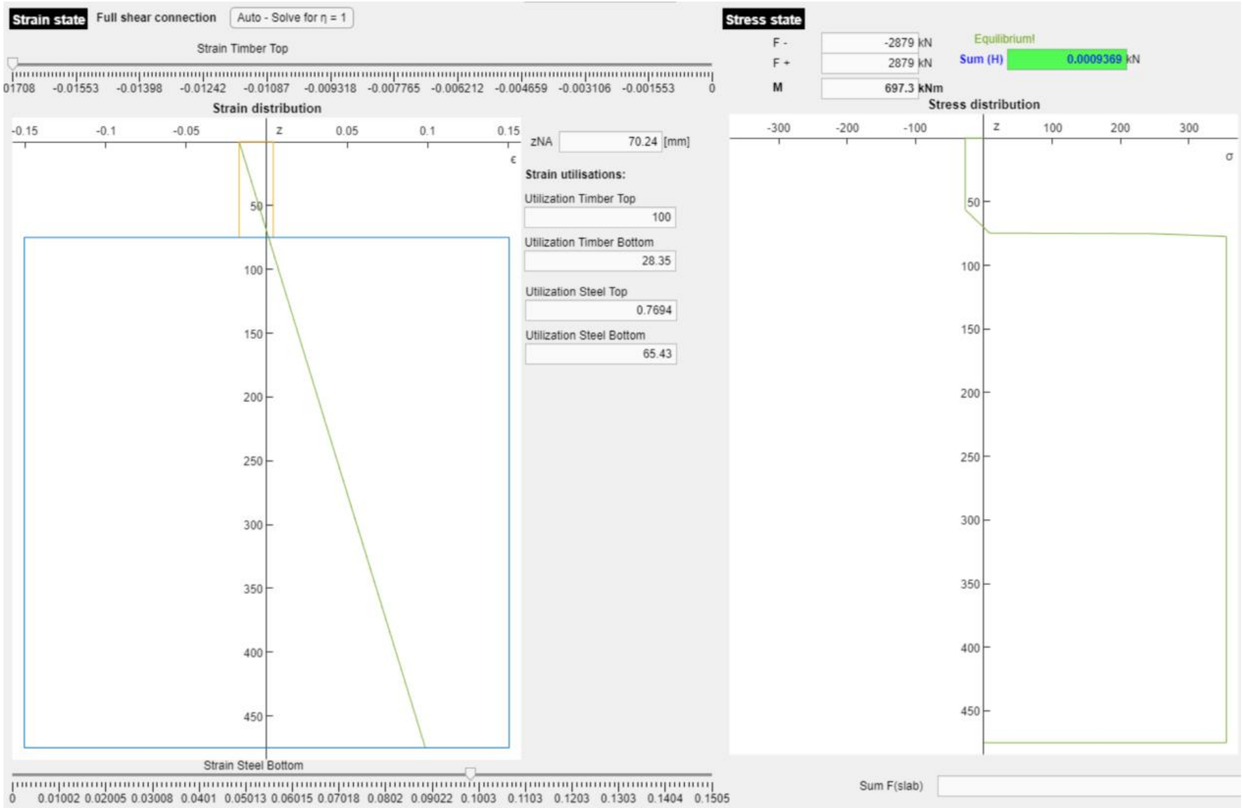


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0146	0.0041	0.0041	0.1036	-2.8641e+03	2.8641e+03	-9.9784e-04	1	742.2794
1	-0.0146	0.0041	0.0150	0.1146	-2.8641e+03	2.8641e+03	-9.9784e-04	1	742.2794
2	-0.0146	0.0041	0.0150	0.1146	-2.8641e+03	2.8641e+03	-9.9784e-04	1	742.2794
3	-0.0146	0.0041	0.0150	0.1146	-2.8641e+03	2.8641e+03	-9.9784e-04	1	742.2794
4	-0.0111	0.0041	-6.7345e-04	0.0802	-2.3426e+03	2.3416e+03	-0.9992	0.8179	728.4781
5	-0.0076	0.0041	-0.0020	0.0602	-1.5082e+03	1.5072e+03	-0.9992	0.5266	698.6008
6	-0.0041	0.0041	-0.0225	0.0211	40.8500	-39.8577	0.9923	-0.0143	504.9118

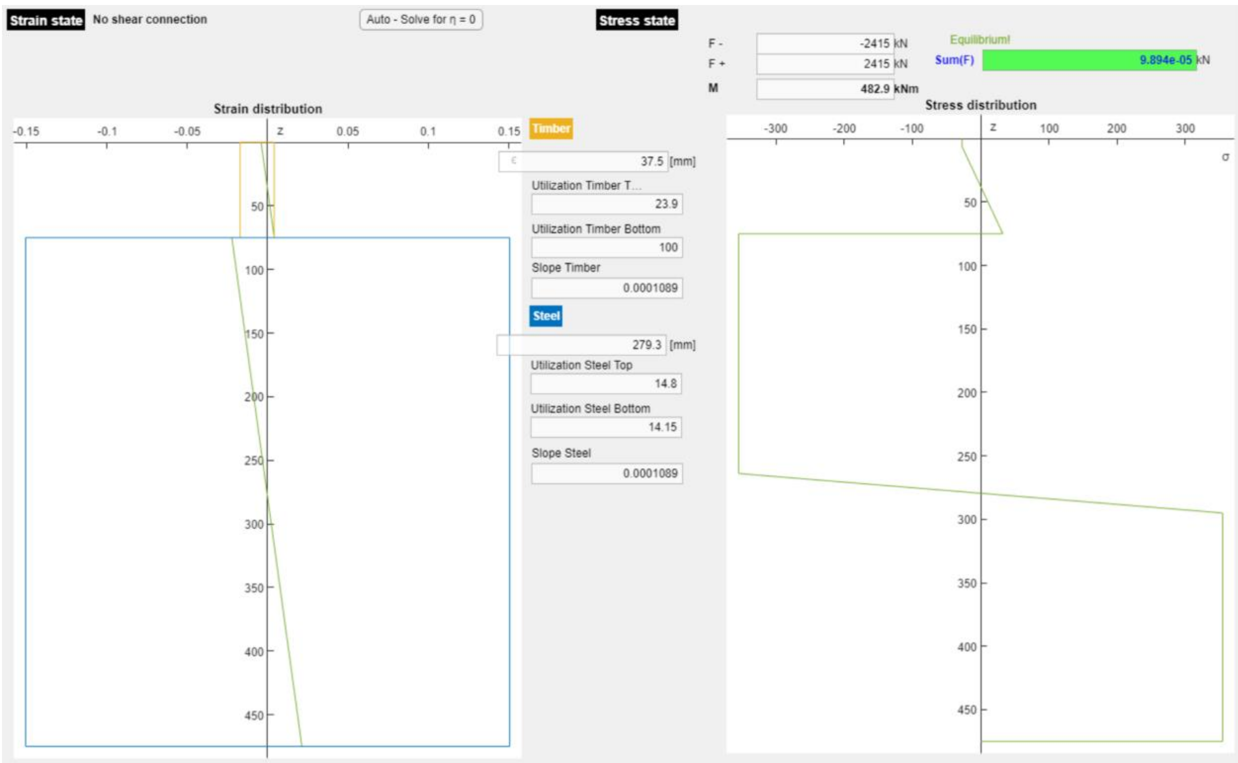


IPE 400, S355, t=1666x75

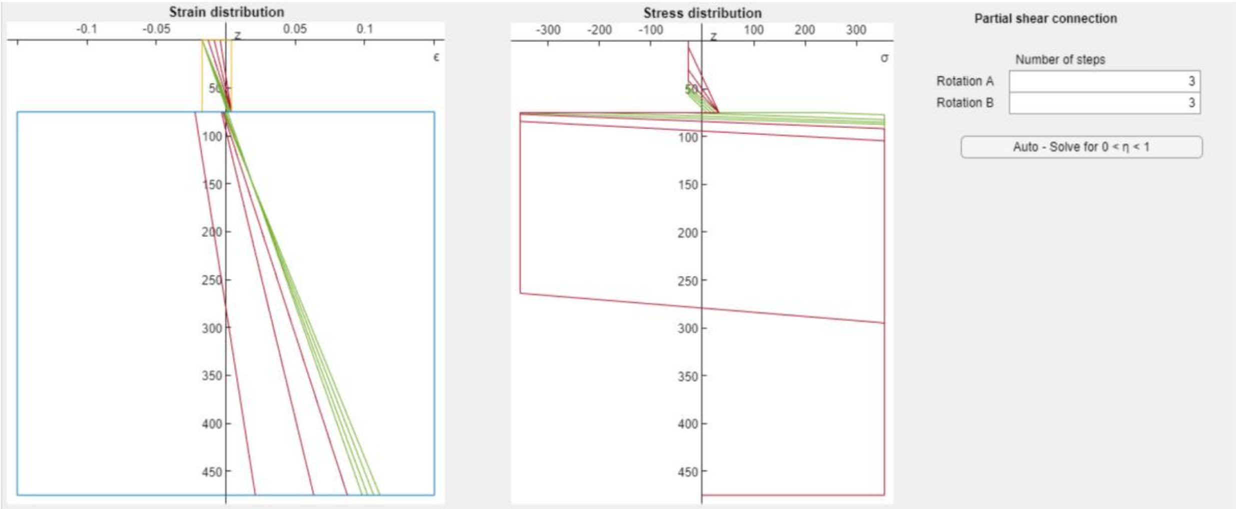
Results for full shear connection:



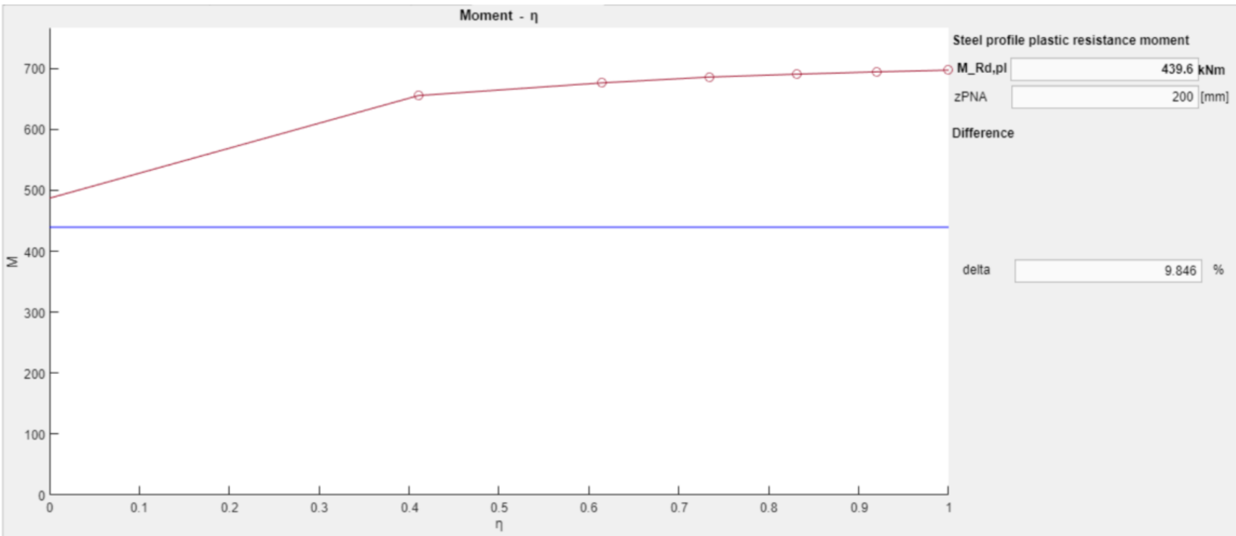
Results for no shear connection:



Results for partial shear connection:

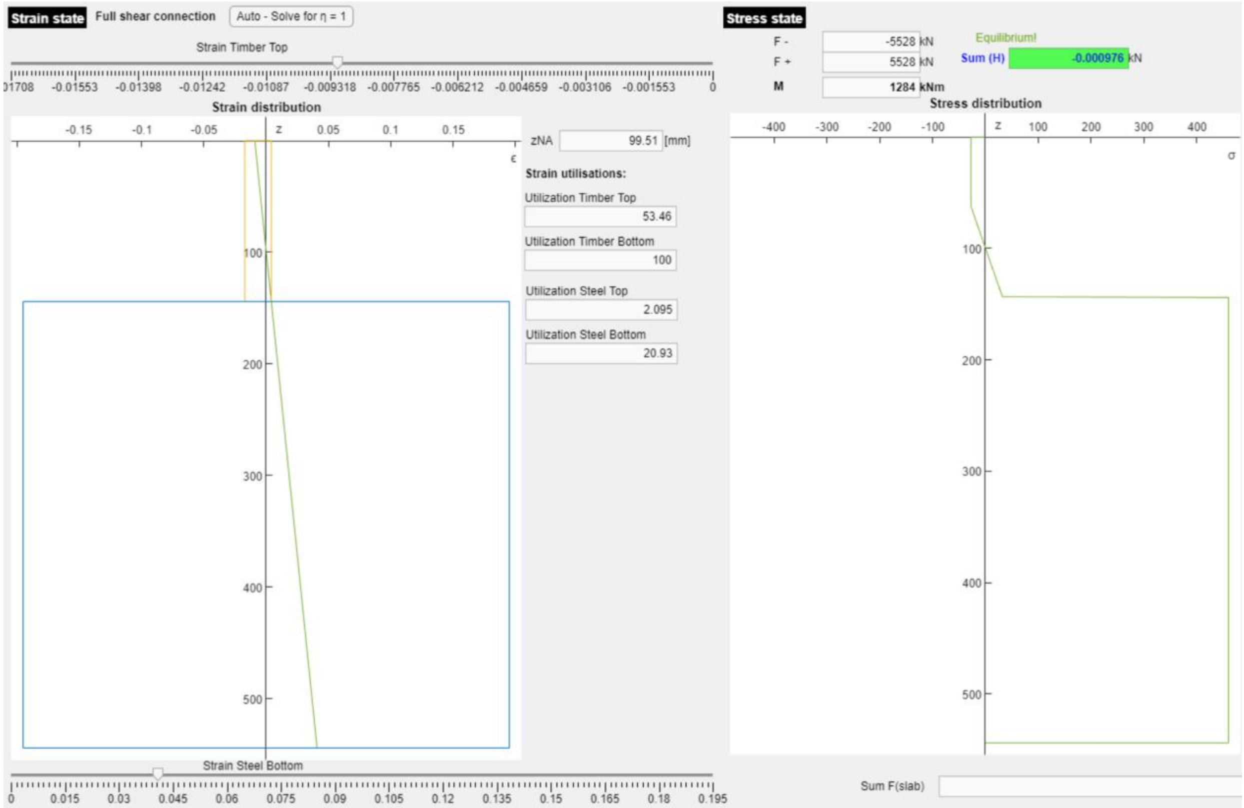


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0171	0.0012	0.0012	0.0984	-2.8420e+03	2.8420e+03	9.3693e-04	1	697.2761
1	-0.0171	0.0021	-1.5319e-04	0.1023	-2.6143e+03	2.6133e+03	-0.9993	0.9199	694.4251
2	-0.0171	0.0031	-9.8778e-04	0.1067	-2.3614e+03	2.3605e+03	-0.9950	0.8309	690.6262
3	-0.0171	0.0041	-0.0017	0.1112	-2.0871e+03	2.0861e+03	-0.9918	0.7344	685.9114
4	-0.0128	0.0041	-0.0020	0.0877	-1.7452e+03	1.7442e+03	-0.9834	0.6141	676.3106
5	-0.0084	0.0041	-0.0032	0.0635	-1.1662e+03	1.1652e+03	-0.9975	0.4103	655.4922
6	-0.0041	0.0041	-0.0222	0.0213	27.2224	-26.2413	0.9812	-0.0096	483.1615

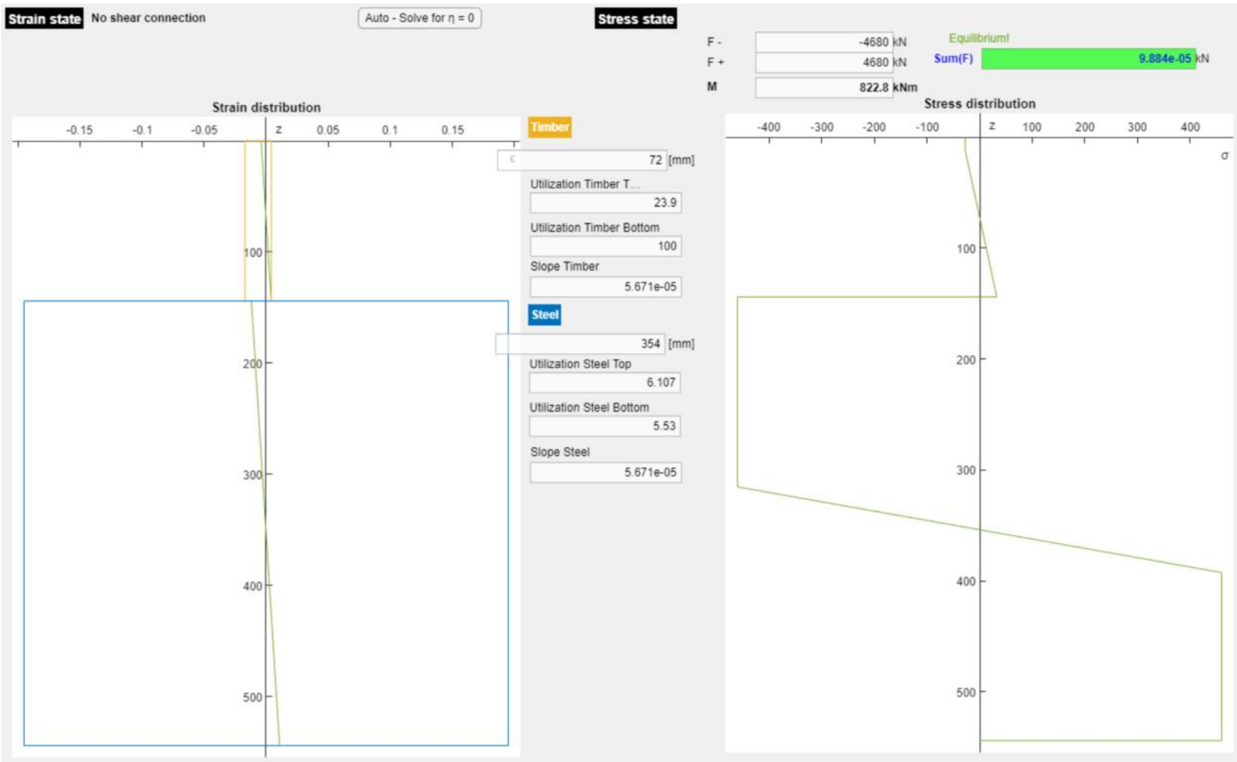


IPE 400, S460, t=2500x144

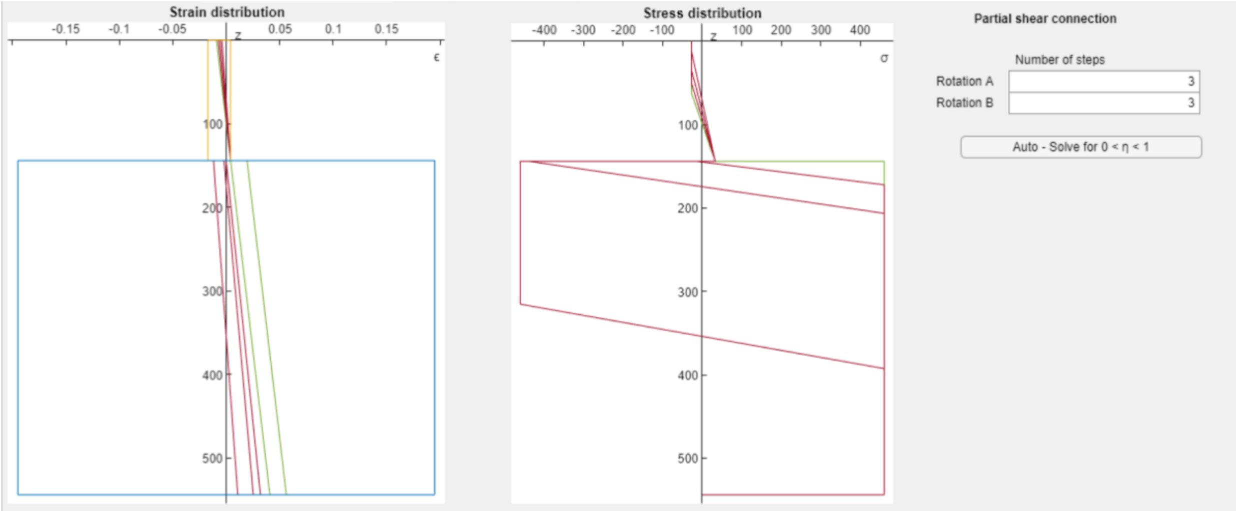
Results for full shear connection:



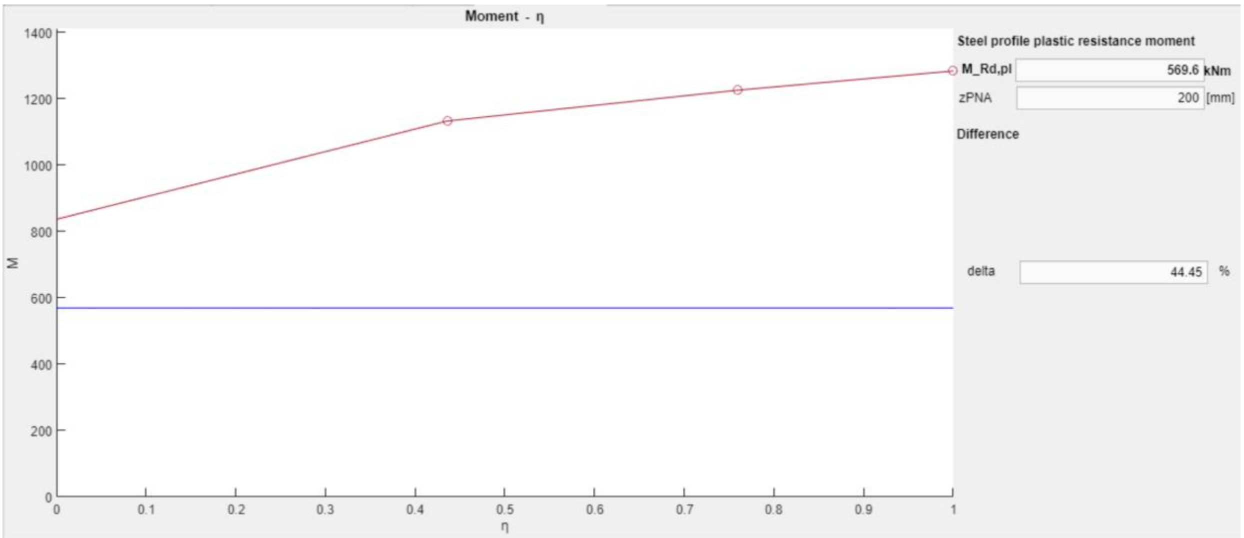
Results for no shear connection:



Results for partial shear connection:

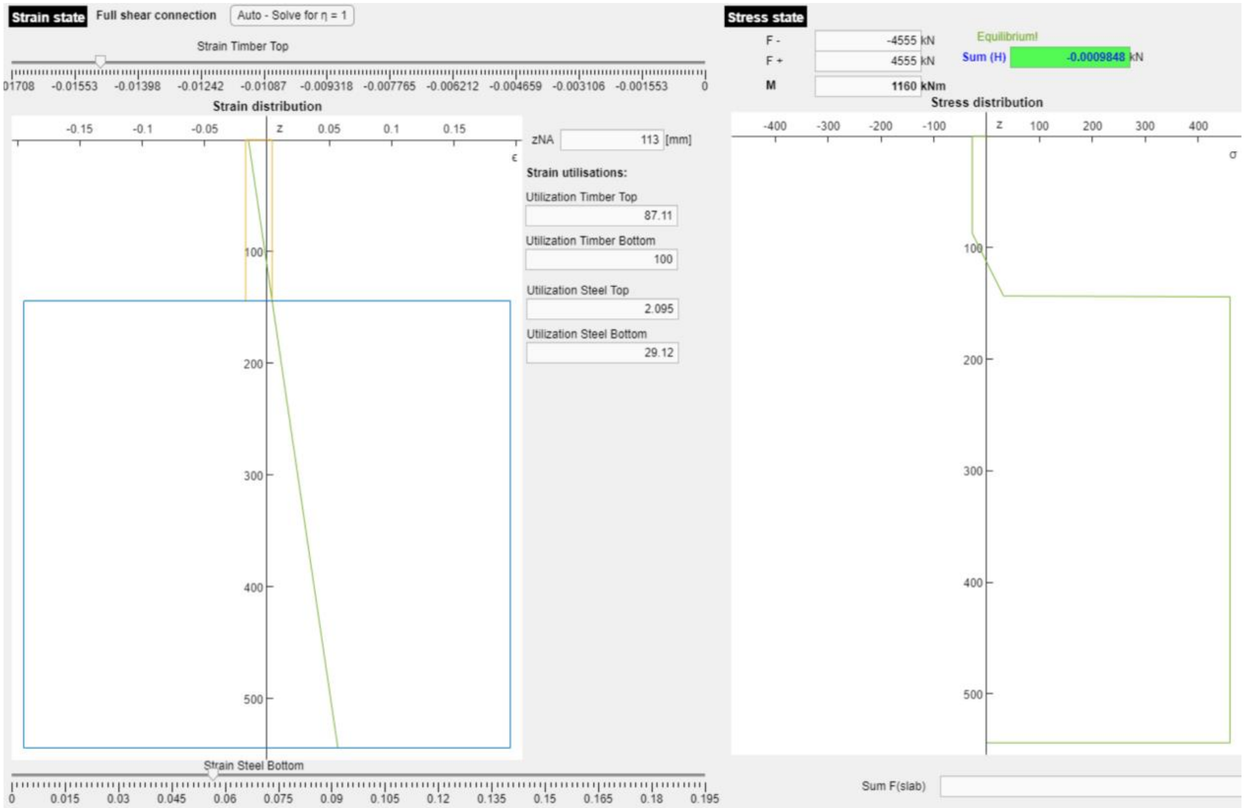


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0091	0.0041	0.0041	0.0408	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
1	-0.0091	0.0041	0.0195	0.0562	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
2	-0.0091	0.0041	0.0195	0.0562	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
3	-0.0091	0.0041	0.0195	0.0562	-3.7112e+03	3.7112e+03	-9.7596e-04	1	1.2838e+03
4	-0.0074	0.0041	-7.3843e-05	0.0320	-2.8168e+03	2.8158e+03	-0.9996	0.7590	1.2257e+03
5	-0.0058	0.0041	-0.0021	0.0253	-1.6165e+03	1.6155e+03	-0.9994	0.4356	1.1330e+03
6	-0.0041	0.0041	-0.0119	0.0108	78.4320	-79.4300	-0.9980	-0.0211	822.4785

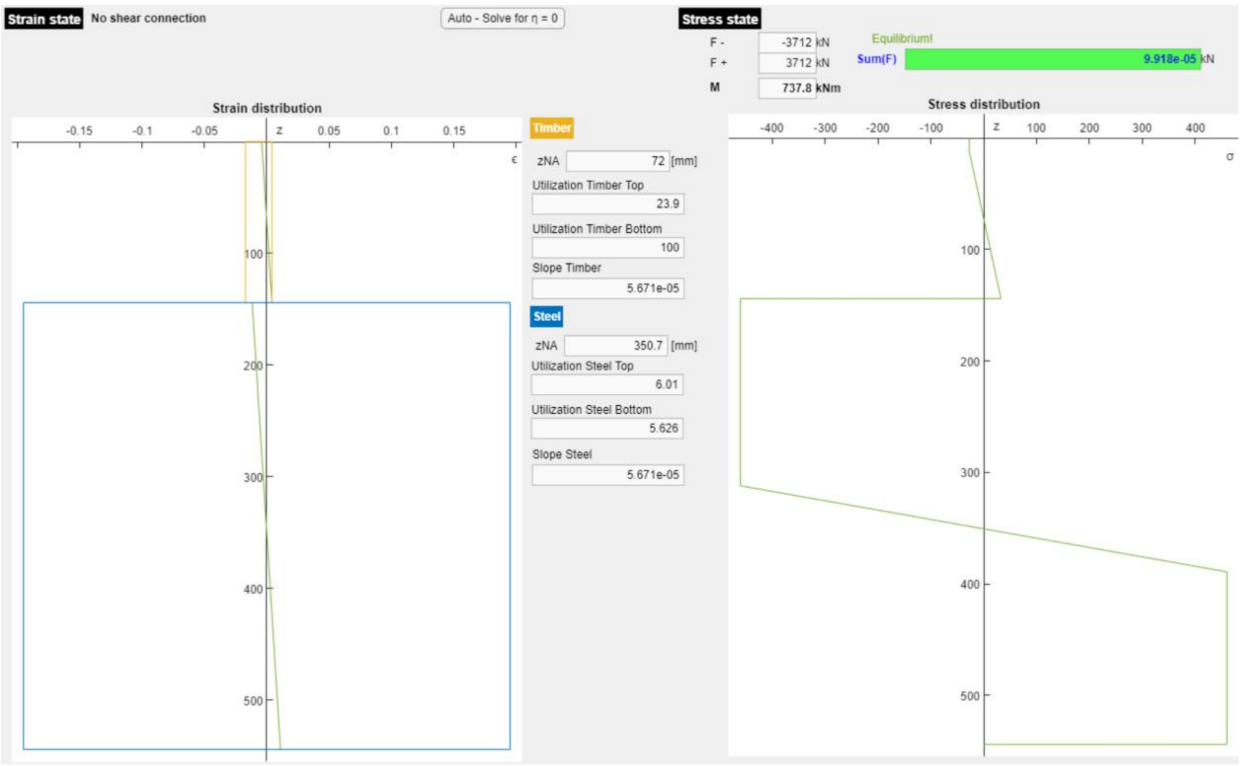


IPE 400, S460, t=1666x144

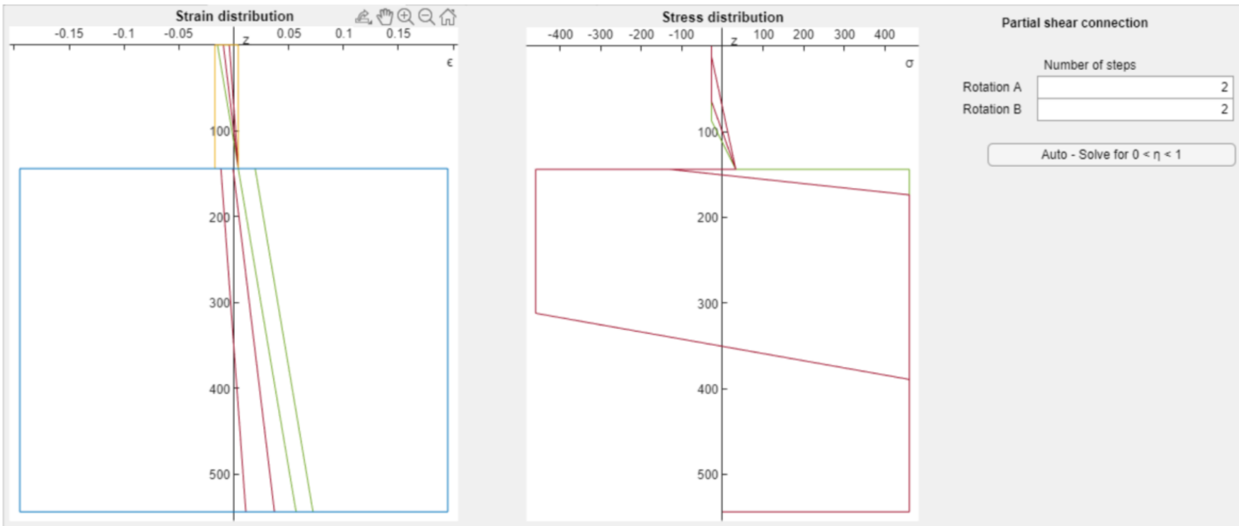
<u>Results for full shear connection:</u>



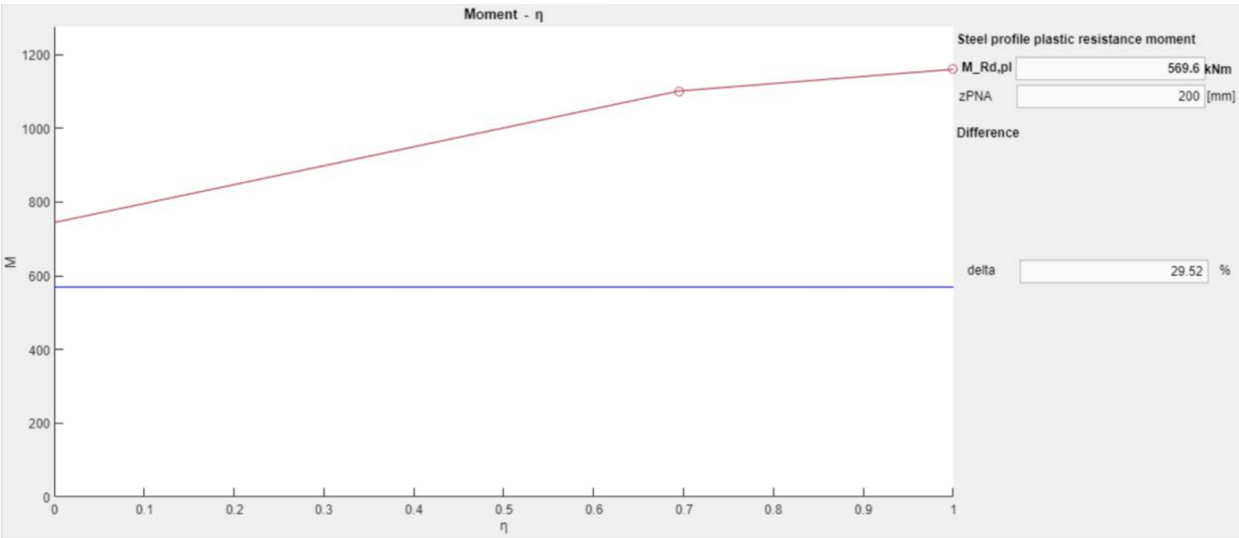
<u>Results for no shear connection:</u>



Results for partial shear connection:

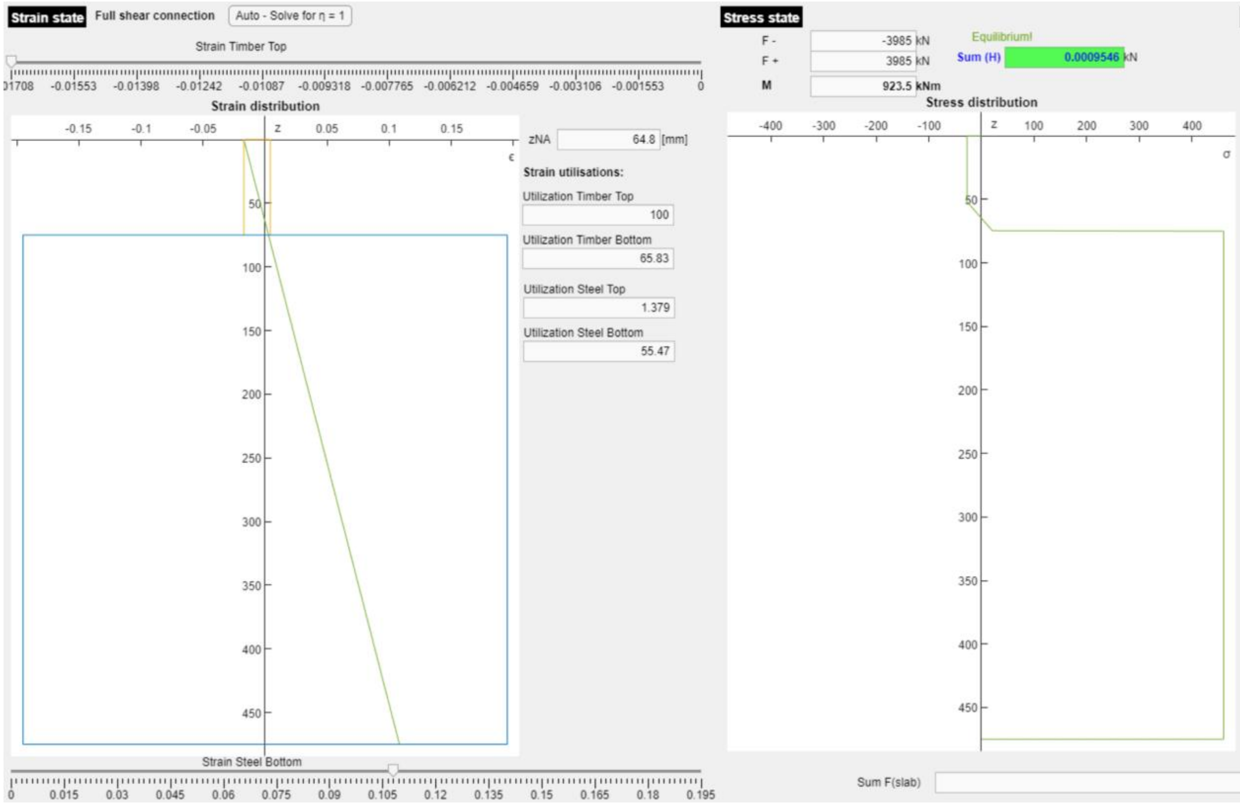


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0149	0.0041	0.0041	0.0568	-3.7112e+03	3.7112e+03	-9.8482e-04	1	1.1603e+03
1	-0.0149	0.0041	0.0195	0.0722	-3.7112e+03	3.7112e+03	-9.8482e-04	1	1.1603e+03
2	-0.0149	0.0041	0.0195	0.0722	-3.7112e+03	3.7112e+03	-9.8482e-04	1	1.1603e+03
3	-0.0095	0.0041	-6.2268e-04	0.0371	-2.5784e+03	2.5774e+03	-0.9977	0.6948	1.1014e+03
4	-0.0041	0.0041	-0.0117	0.0110	52.2671	-53.2595	-0.9924	-0.0141	737.4450

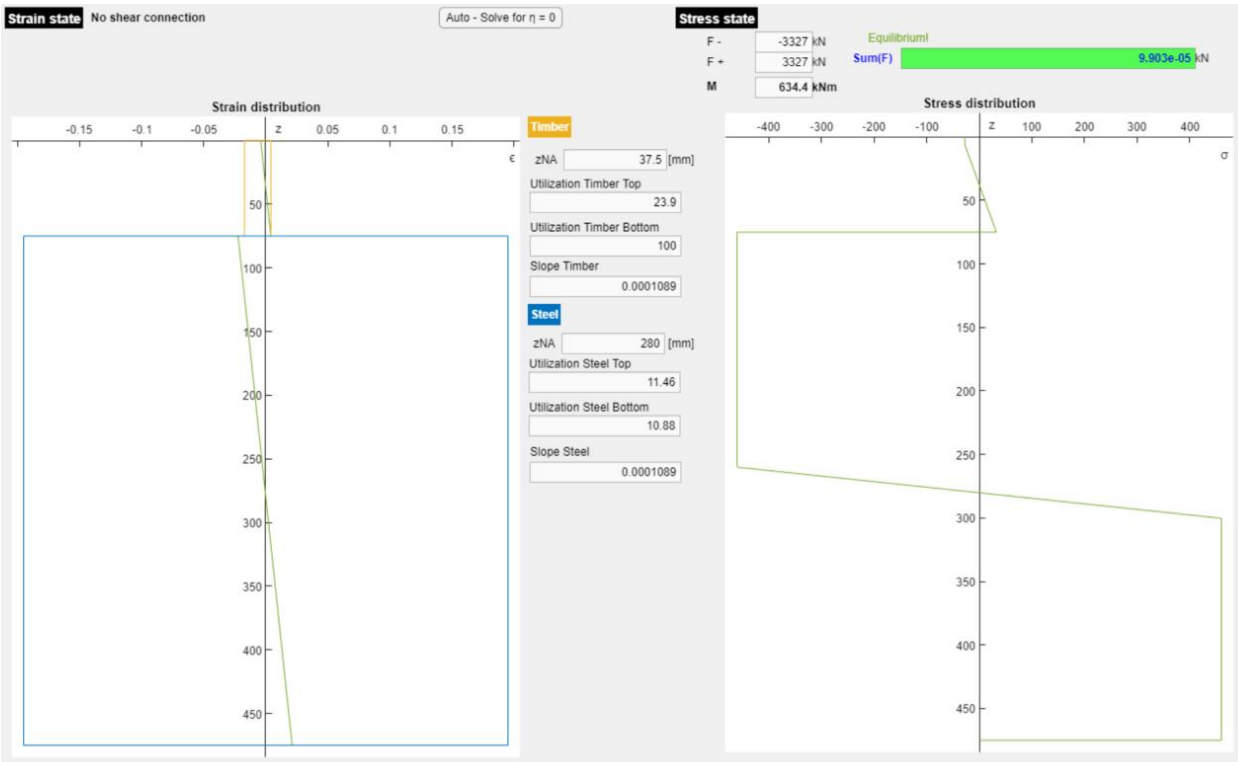


IPE 400, S460, t=2500x75

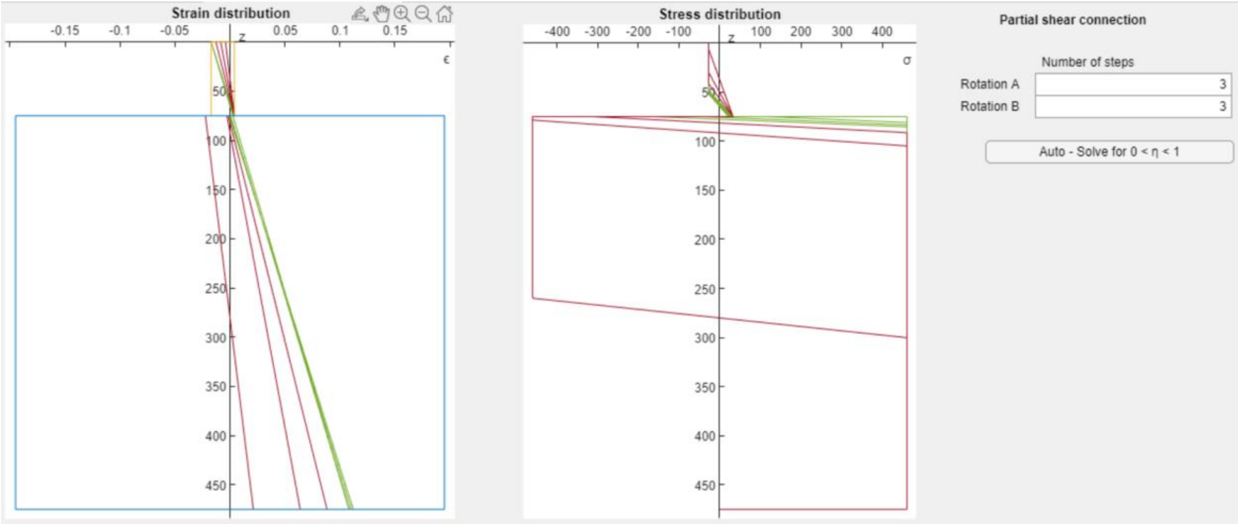
Results for full shear connection:



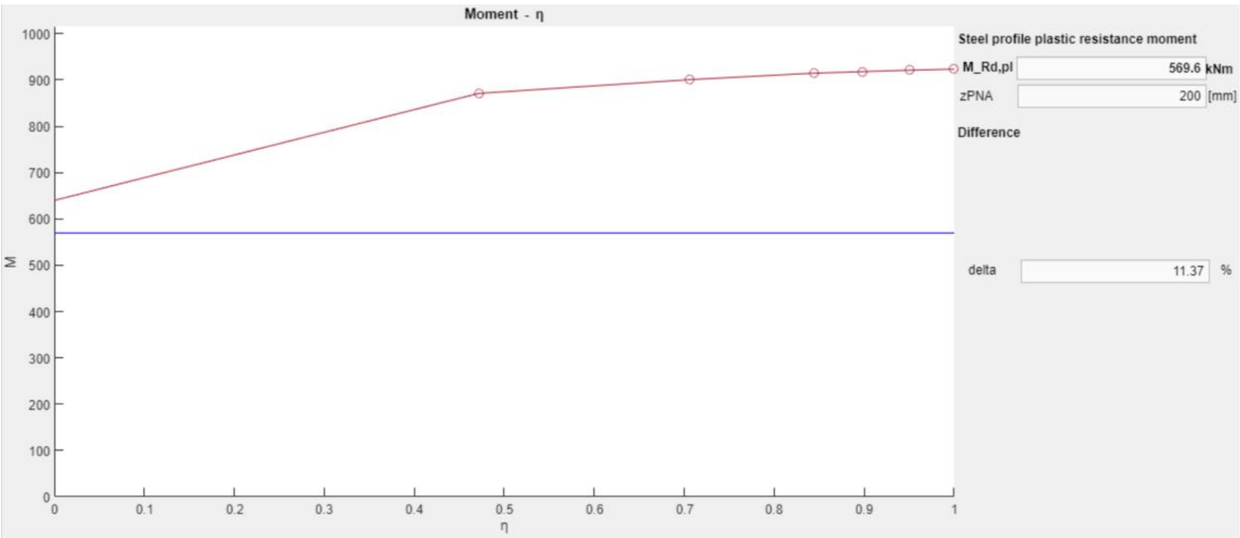
Results for no shear connection:



Results for partial shear connection:

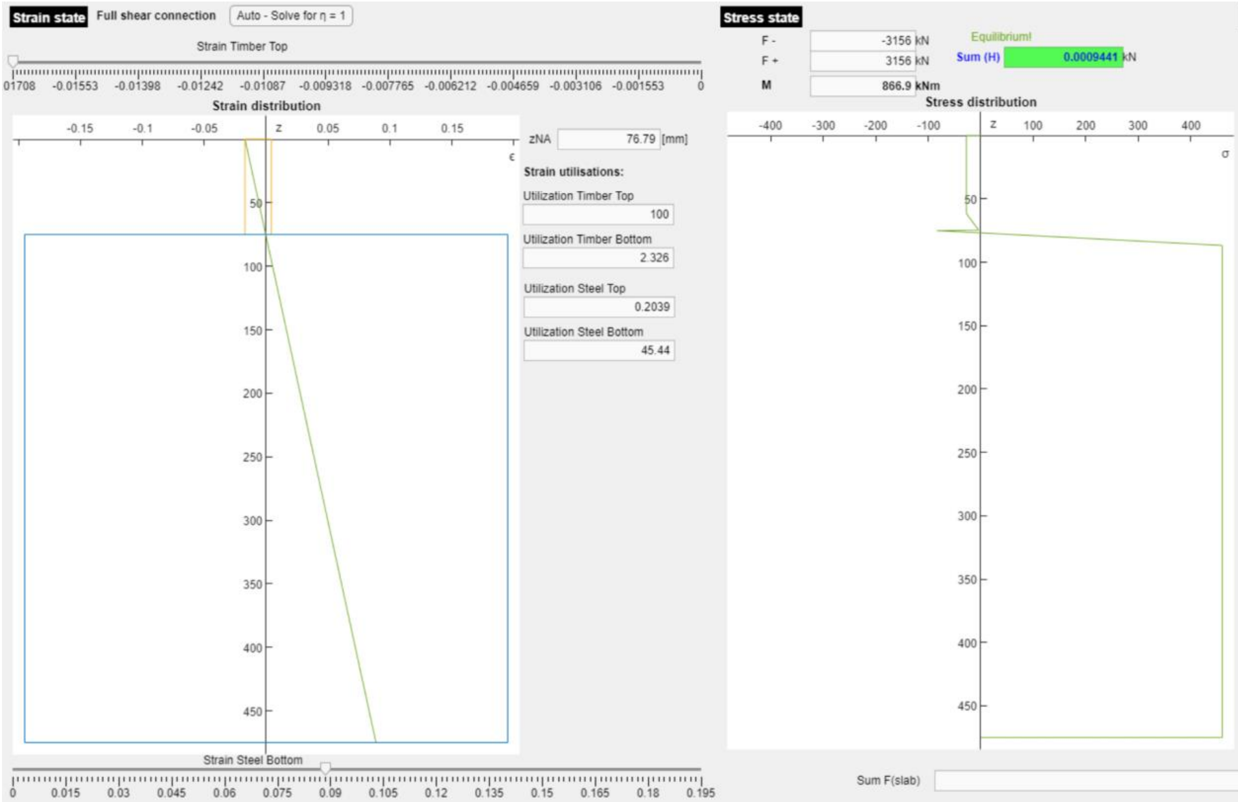


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0171	0.0027	0.0027	0.1081	-3.7112e+03	3.7112e+03	9.5463e-04	1	923.5093
1	-0.0171	0.0032	5.6600e-04	0.1085	-3.5253e+03	3.5263e+03	0.9989	0.9499	921.1419
2	-0.0171	0.0036	-1.6562e-04	0.1102	-3.3320e+03	3.3310e+03	-0.9998	0.8978	918.0322
3	-0.0171	0.0041	-7.5308e-04	0.1121	-3.1318e+03	3.1308e+03	-0.9981	0.8439	914.6723
4	-0.0128	0.0041	-0.0015	0.0883	-2.6188e+03	2.6178e+03	-0.9939	0.7056	900.7781
5	-0.0084	0.0041	-0.0028	0.0639	-1.7500e+03	1.7490e+03	-0.9906	0.4715	871.0642
6	-0.0041	0.0041	-0.0223	0.0212	40.8500	-39.8645	0.9855	-0.0110	634.6748

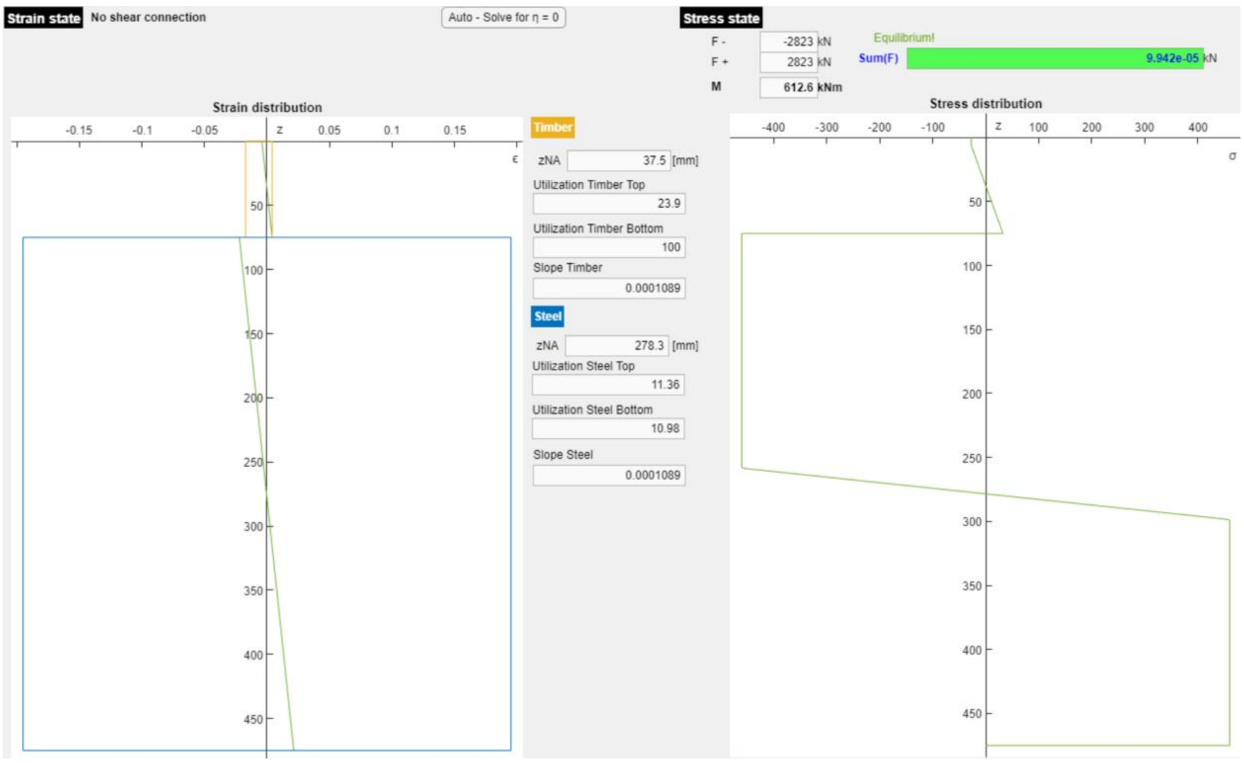


IPE 400, S460, t=1666x75

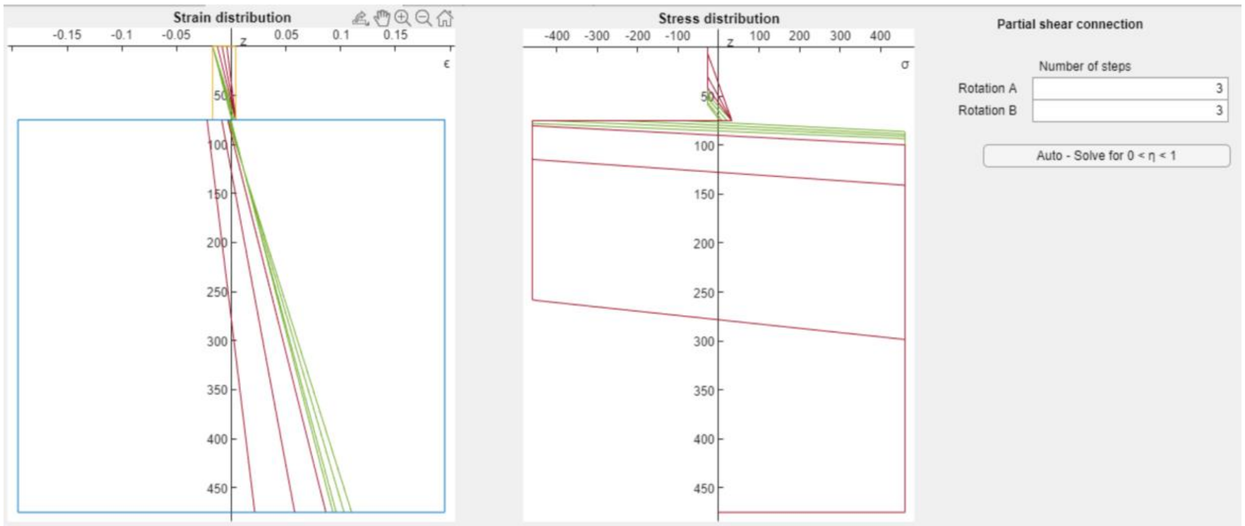
Results for full shear connection:



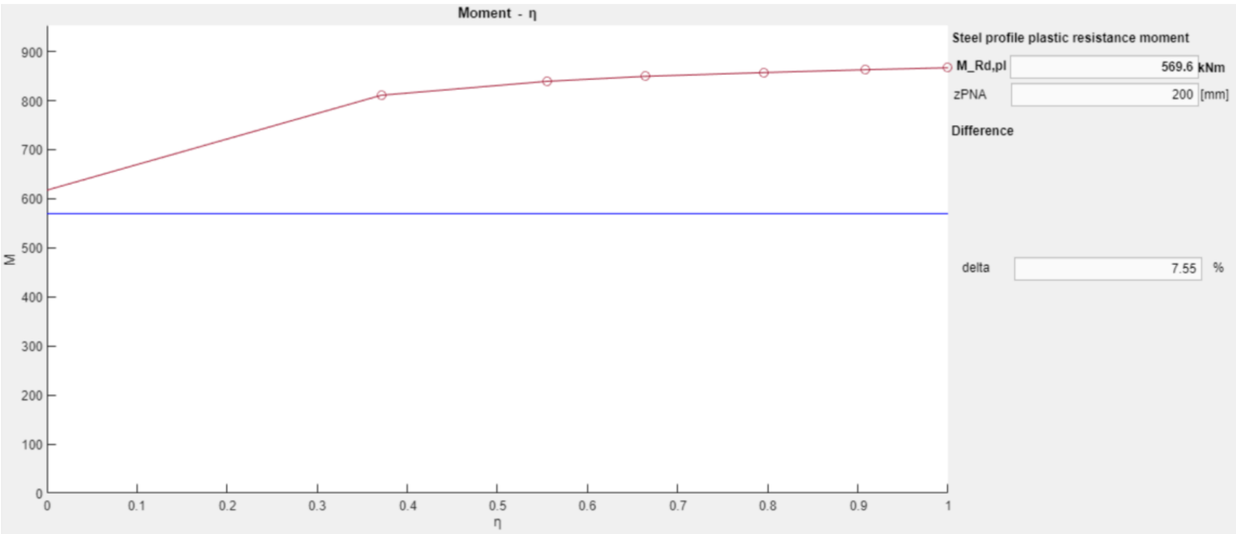
Results for no shear connection:



Results for partial shear connection:

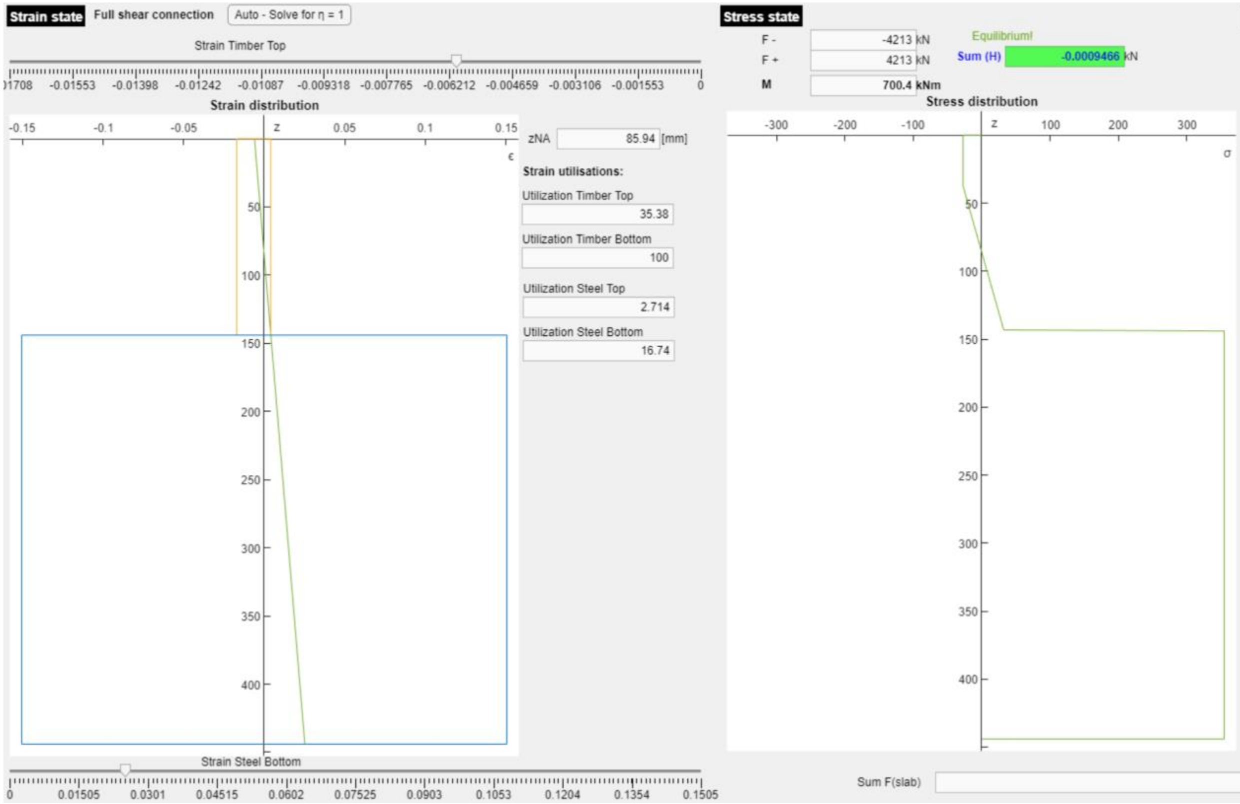


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0171	-3.9743e-04	-3.9743e-04	0.0886	-3.1422e+03	3.1422e+03	9.4406e-04	1	866.8685
1	-0.0171	0.0011	-0.0011	0.0958	-2.8553e+03	2.8543e+03	-0.9997	0.9087	862.8541
2	-0.0171	0.0026	-0.0020	0.1030	-2.4987e+03	2.4977e+03	-0.9947	0.7952	857.0716
3	-0.0171	0.0041	-0.0030	0.1099	-2.0871e+03	2.0861e+03	-0.9987	0.6642	849.4012
4	-0.0128	0.0041	-0.0034	0.0864	-1.7452e+03	1.7442e+03	-0.9821	0.5554	839.2573
5	-0.0084	0.0041	-0.0088	0.0579	-1.1662e+03	1.1652e+03	-0.9964	0.3711	810.9019
6	-0.0041	0.0041	-0.0221	0.0214	27.2224	-26.2382	0.9843	-0.0087	612.9104

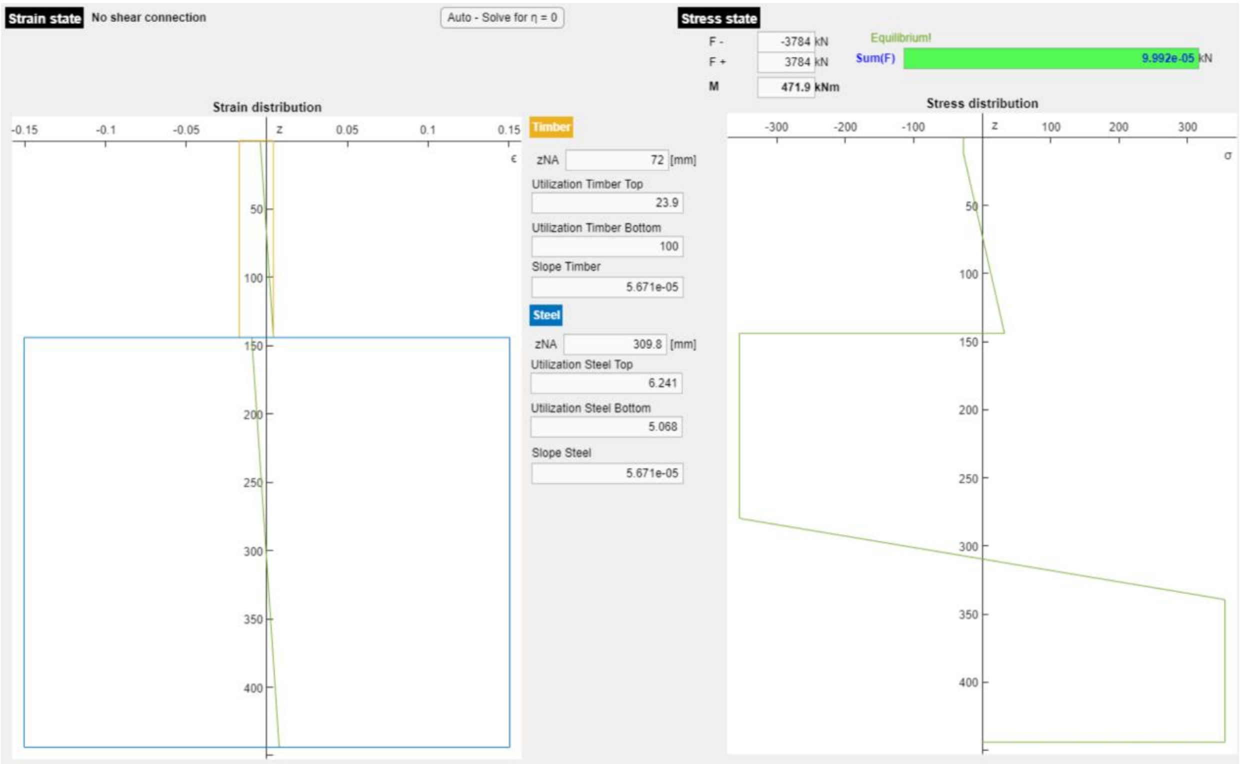


IPE 300, S355, t=2500x144

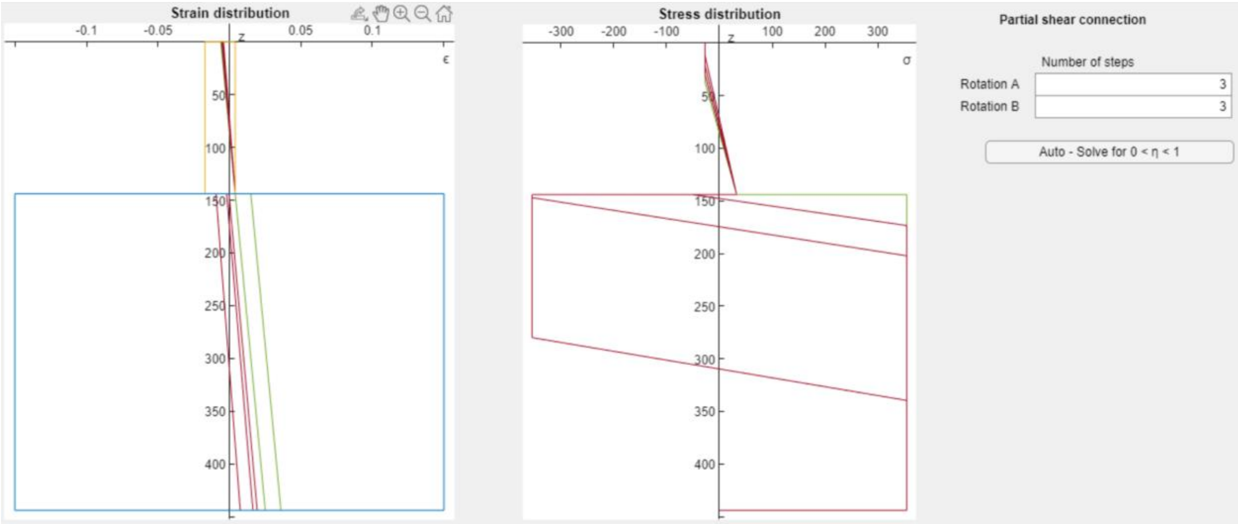
Results for full shear connection:



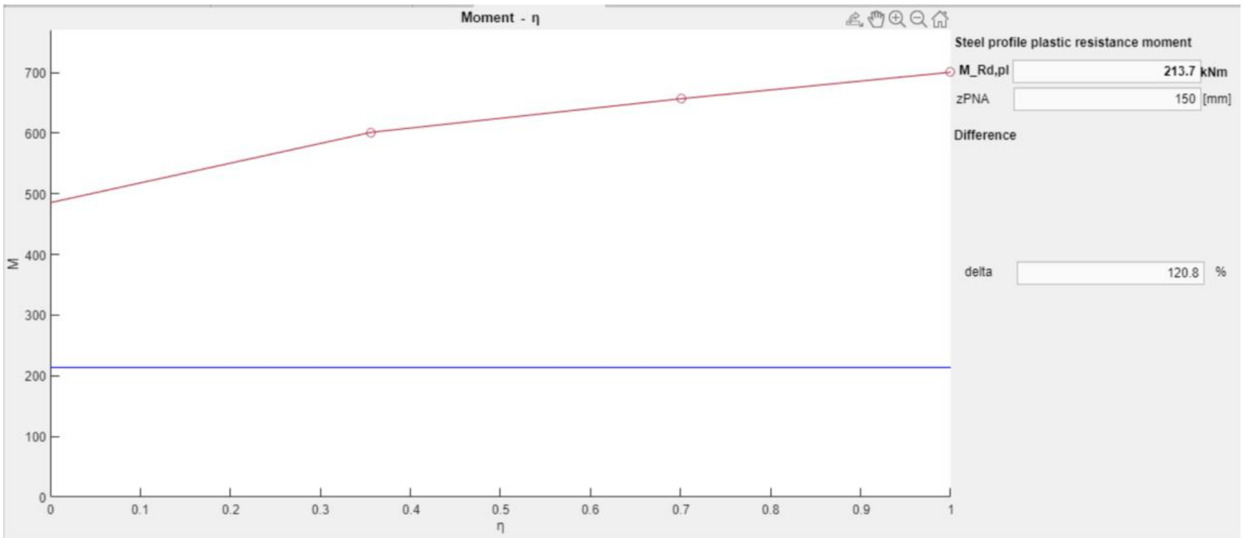
Results for no shear connection:



Results for partial shear connection:

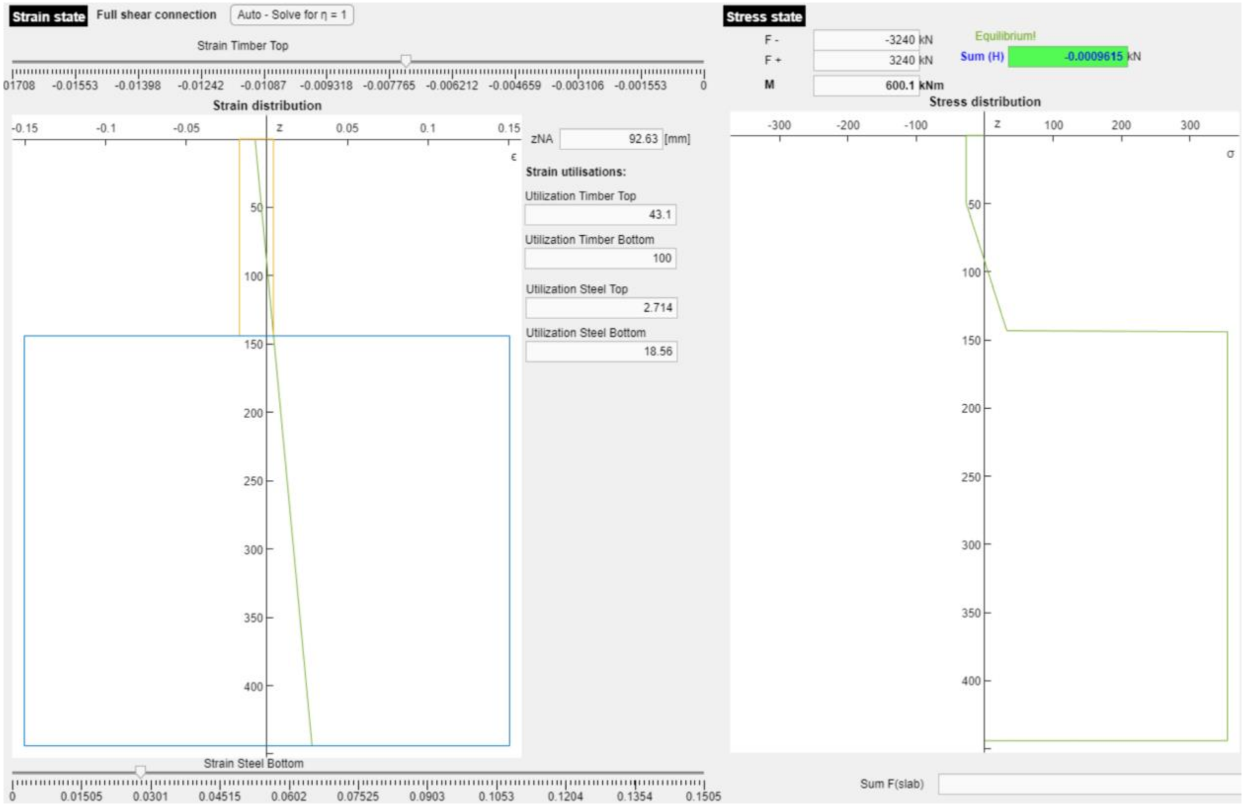


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0060	0.0041	0.0041	0.0252	-1.8418e+03	1.8418e+03	-9.4659e-04	1	700.4165
1	-0.0060	0.0041	0.0150	0.0361	-1.8418e+03	1.8418e+03	-9.4659e-04	1	700.4165
2	-0.0060	0.0041	0.0150	0.0361	-1.8418e+03	1.8418e+03	-9.4659e-04	1	700.4165
3	-0.0060	0.0041	0.0150	0.0361	-1.8418e+03	1.8418e+03	-9.4659e-04	1	700.4165
4	-0.0054	0.0041	-2.5014e-04	0.0195	-1.2900e+03	1.2890e+03	-0.9996	0.7004	656.7410
5	-0.0047	0.0041	-0.0019	0.0165	-656.5196	655.5267	-0.9928	0.3565	601.3889
6	-0.0041	0.0041	-0.0094	0.0076	78.4320	-79.4315	-0.9995	-0.0426	471.5603

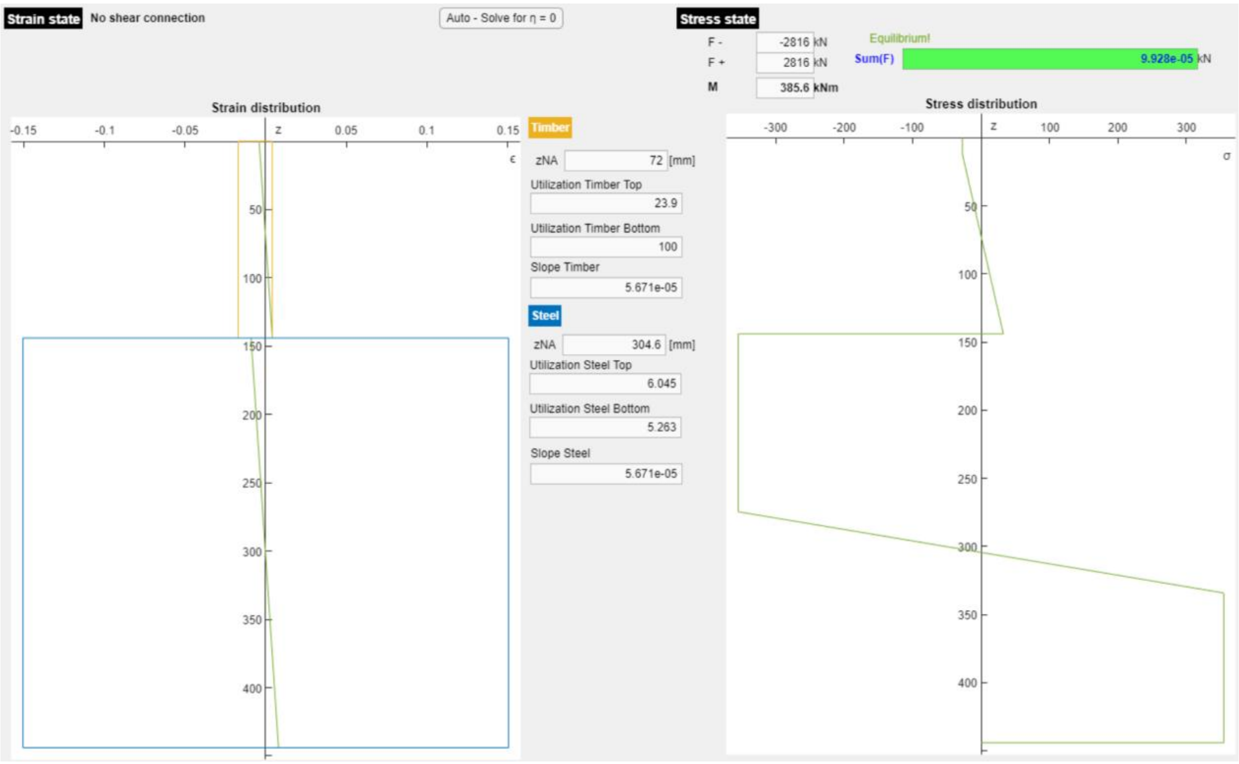


IPE 300, S355, t=1666x144

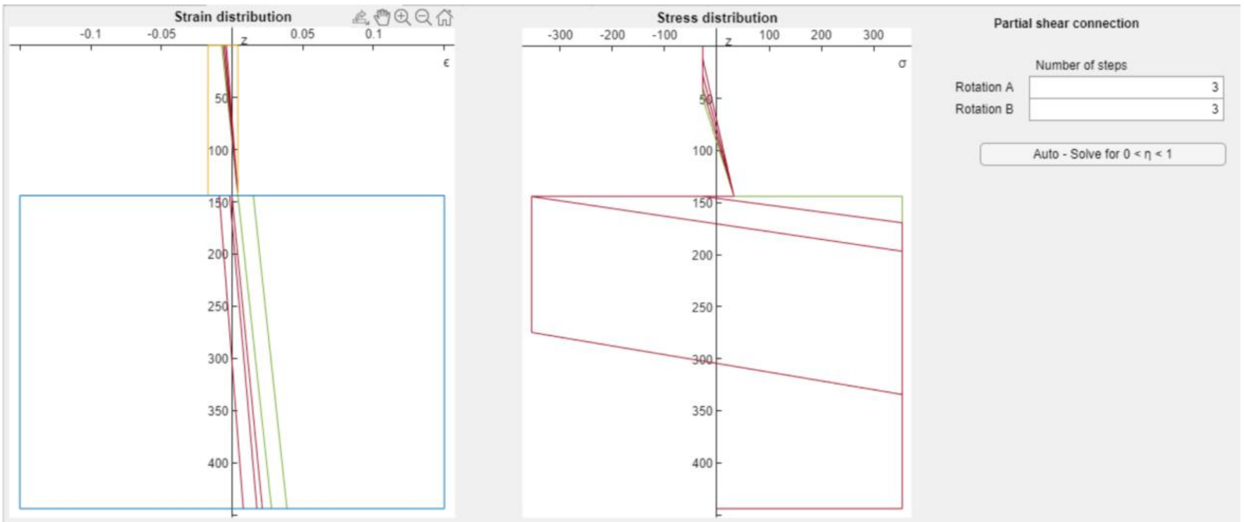
Results for full shear connection:



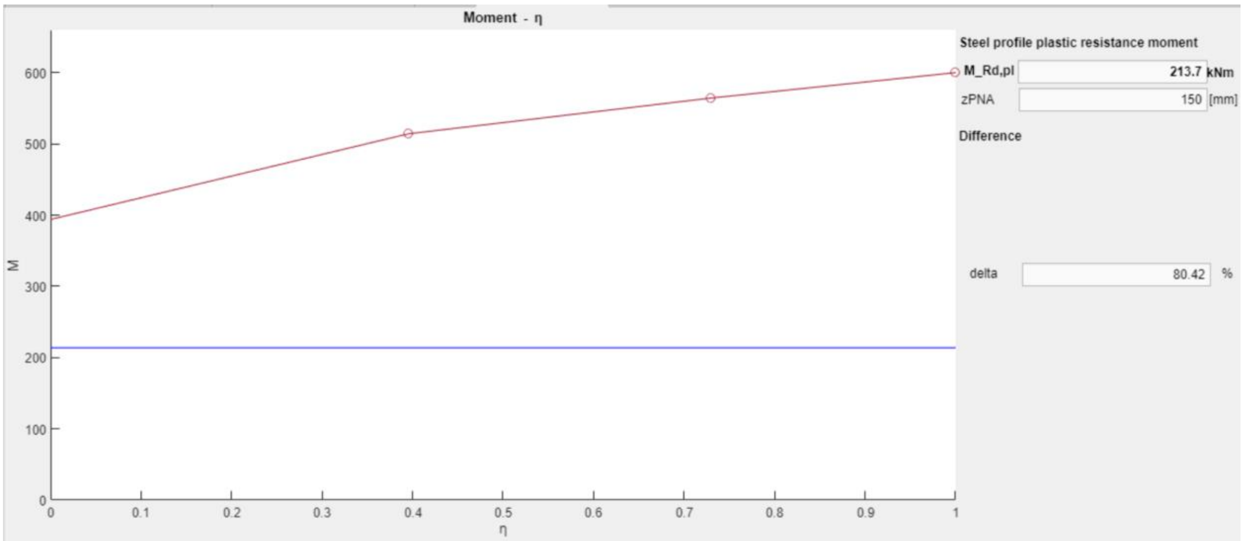
Results for no shear connection:



Results for partial shear connection:

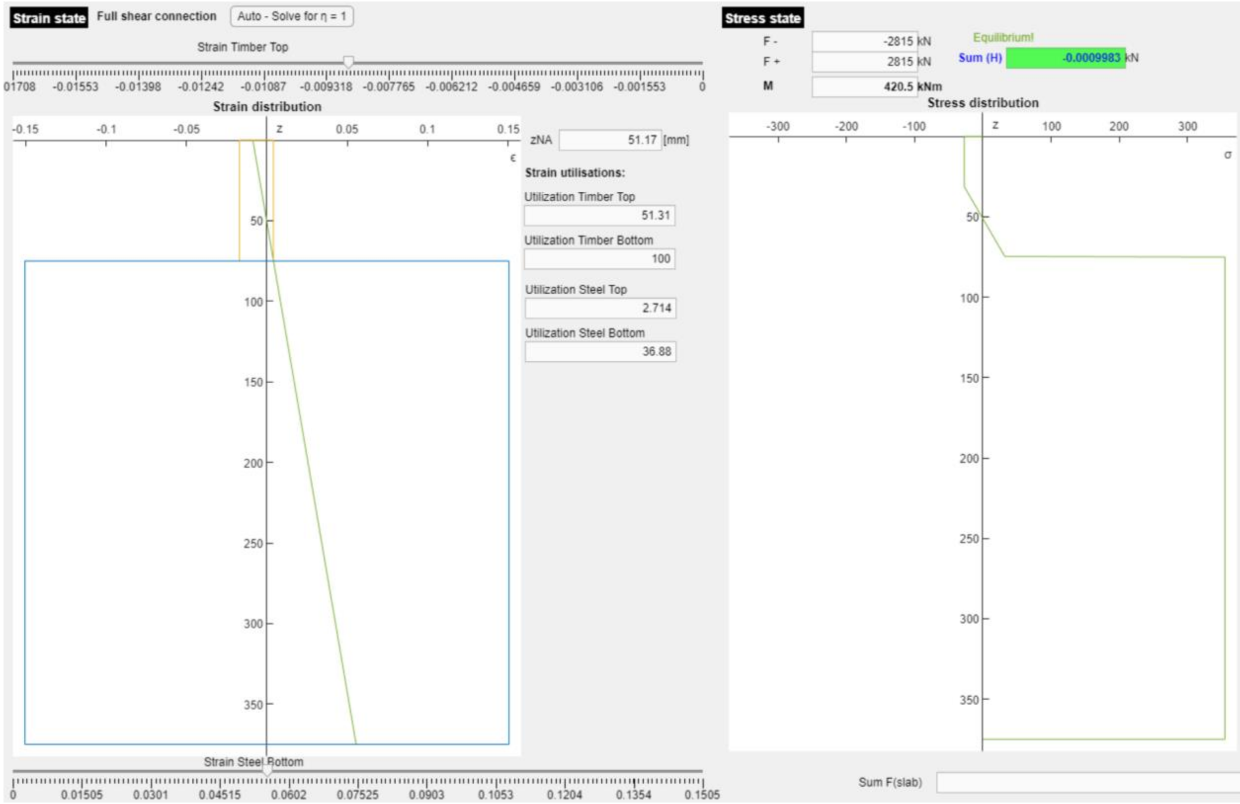


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0074	0.0041	0.0041	0.0279	-1.8418e+03	1.8418e+03	-9.6147e-04	1	600.0840
1	-0.0074	0.0041	0.0150	0.0389	-1.8418e+03	1.8418e+03	-9.6147e-04	1	600.0840
2	-0.0074	0.0041	0.0150	0.0389	-1.8418e+03	1.8418e+03	-9.6147e-04	1	600.0840
3	-0.0074	0.0041	0.0150	0.0389	-1.8418e+03	1.8418e+03	-9.6147e-04	1	600.0840
4	-0.0063	0.0041	-1.4003e-04	0.0214	-1.3438e+03	1.3428e+03	-0.9996	0.7296	564.4024
5	-0.0052	0.0041	-0.0017	0.0176	-728.1929	727.1966	-0.9963	0.3954	514.2182
6	-0.0041	0.0041	-0.0091	0.0079	52.2671	-53.2594	-0.9923	-0.0284	385.3437

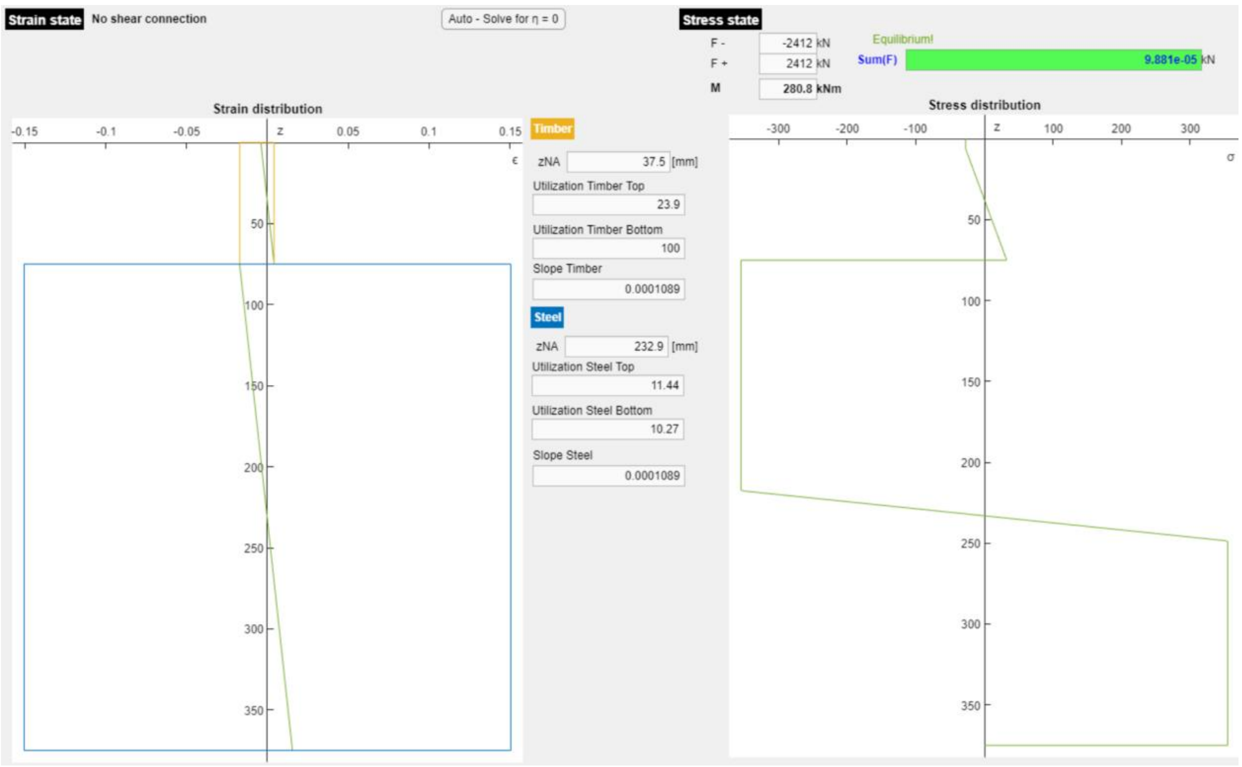


IPE 300, S355, t=2500x75

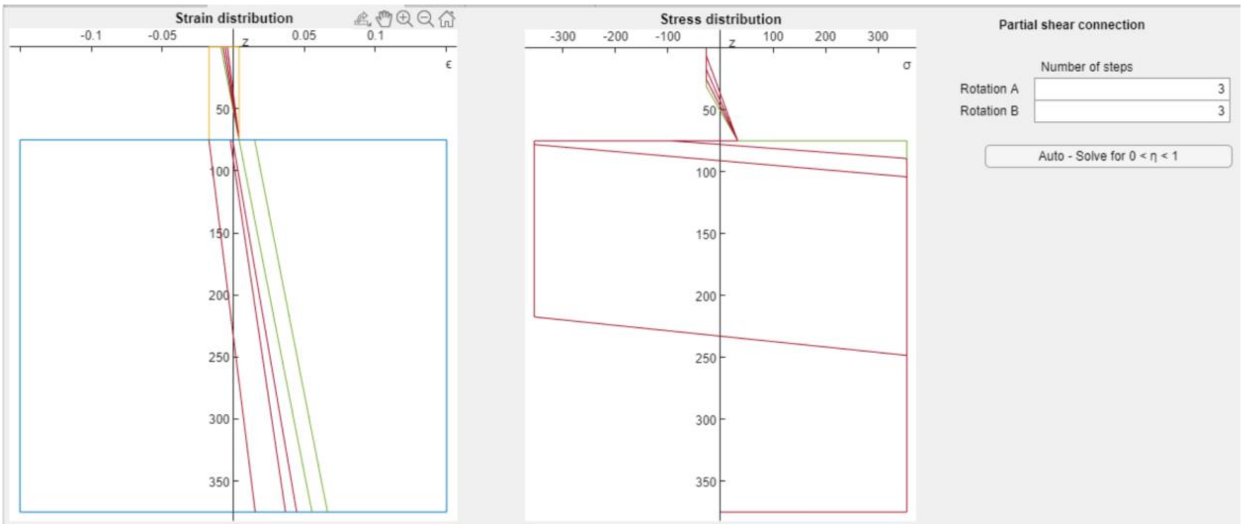
<u>Results for full shear connection:</u>



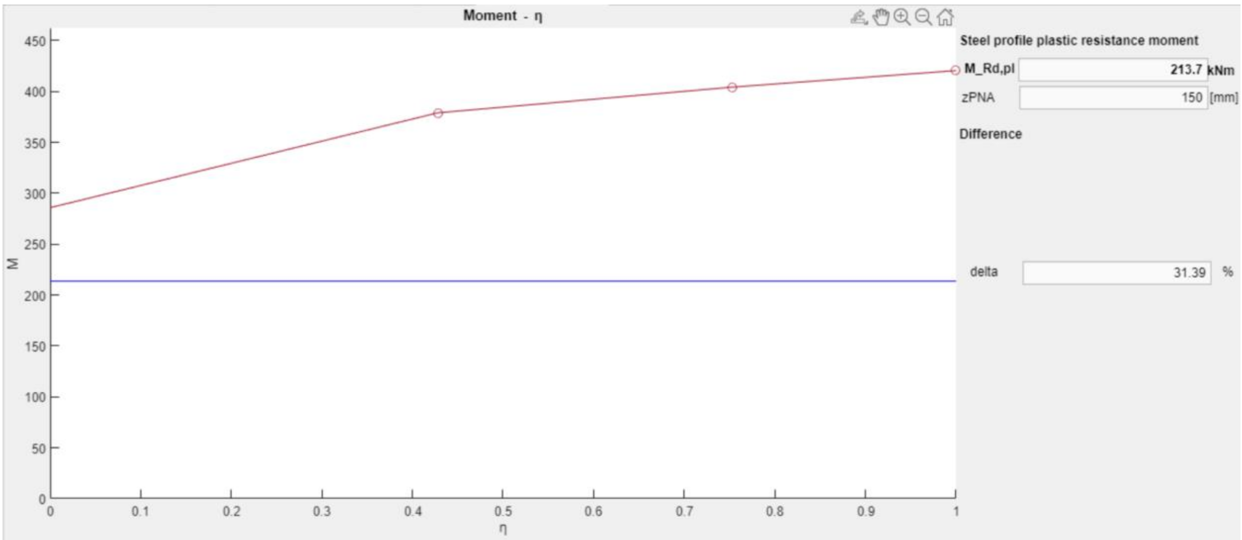
<u>Results for no shear connection:</u>



Results for partial shear connection:

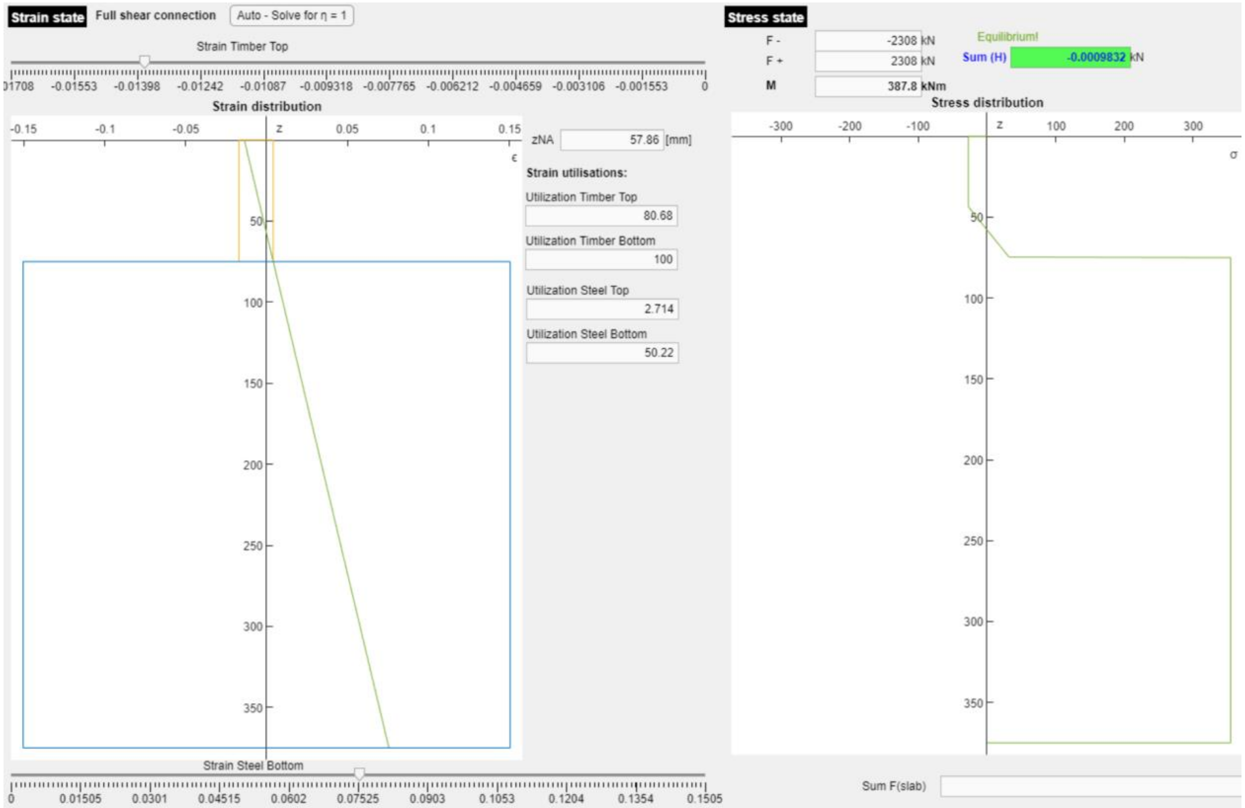


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0088	0.0041	0.0041	0.0555	-1.8418e+03	1.8418e+03	-9.9826e-04	1	420.5395
1	-0.0088	0.0041	0.0150	0.0664	-1.8418e+03	1.8418e+03	-9.9826e-04	1	420.5395
2	-0.0088	0.0041	0.0150	0.0664	-1.8418e+03	1.8418e+03	-9.9826e-04	1	420.5395
3	-0.0088	0.0041	0.0150	0.0664	-1.8418e+03	1.8418e+03	-9.9826e-04	1	420.5395
4	-0.0072	0.0041	-4.6031e-04	0.0447	-1.3878e+03	1.3868e+03	-0.9995	0.7535	404.3403
5	-0.0056	0.0041	-0.0021	0.0368	-788.0953	787.0969	-0.9984	0.4279	379.0897
6	-0.0041	0.0041	-0.0172	0.0155	40.8500	-39.8647	0.9853	-0.0222	281.0591

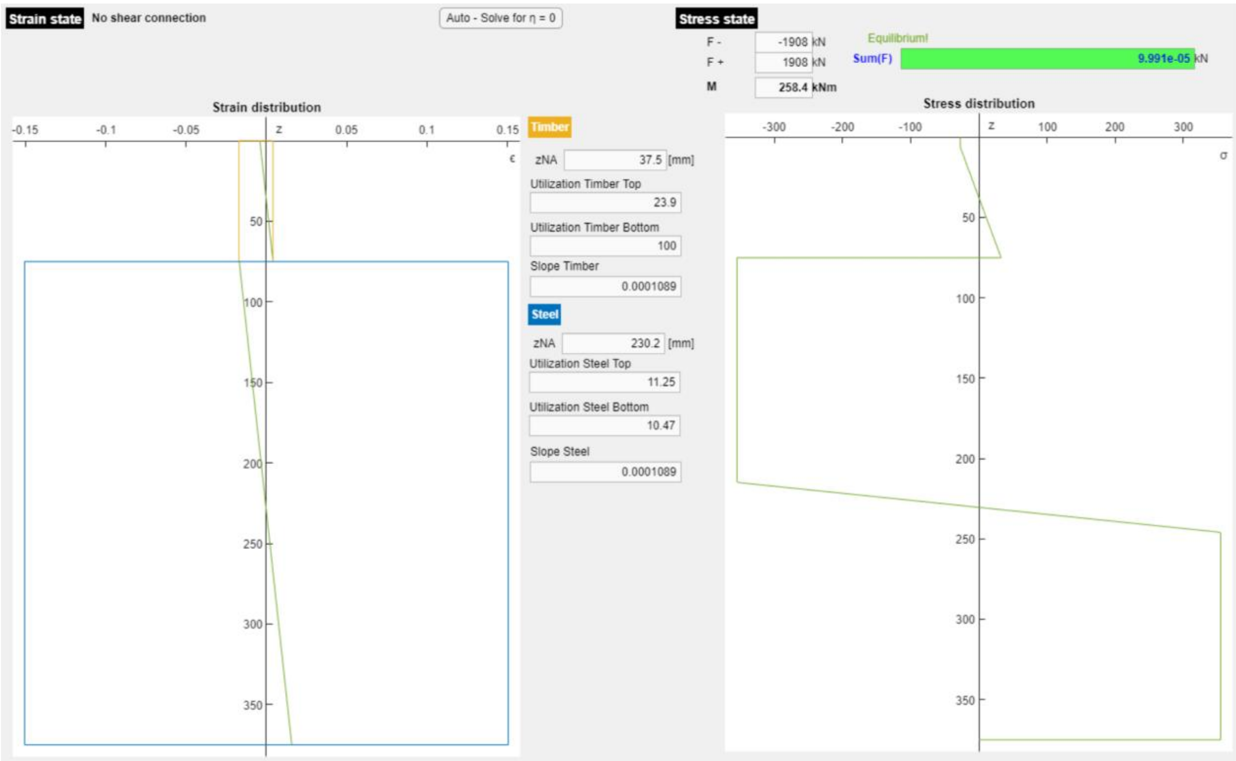


IPE 300, S355, t=1666x75

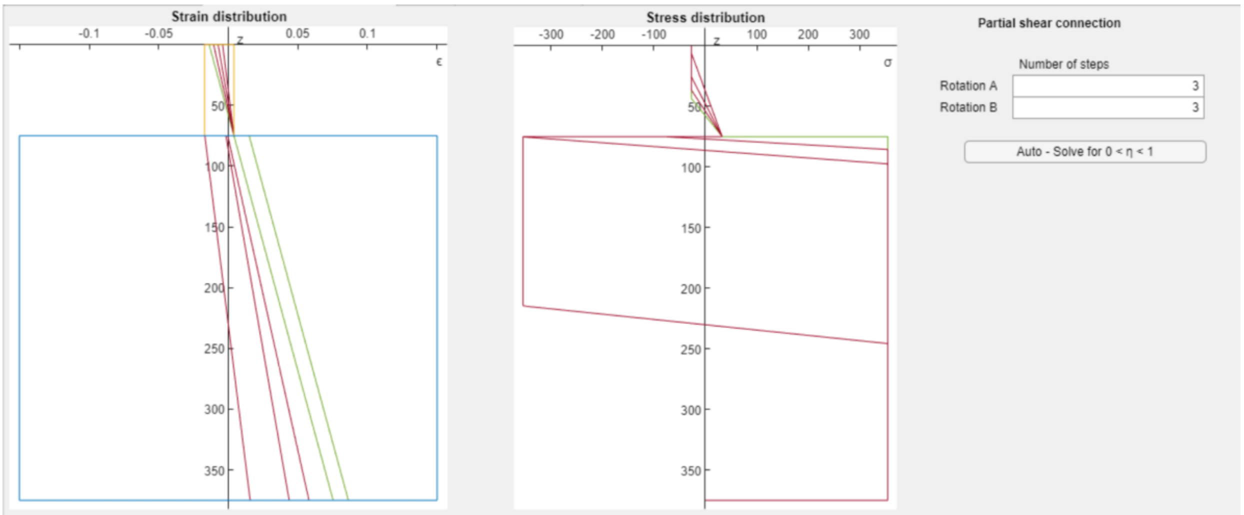
<u>Results for full shear connection:</u>



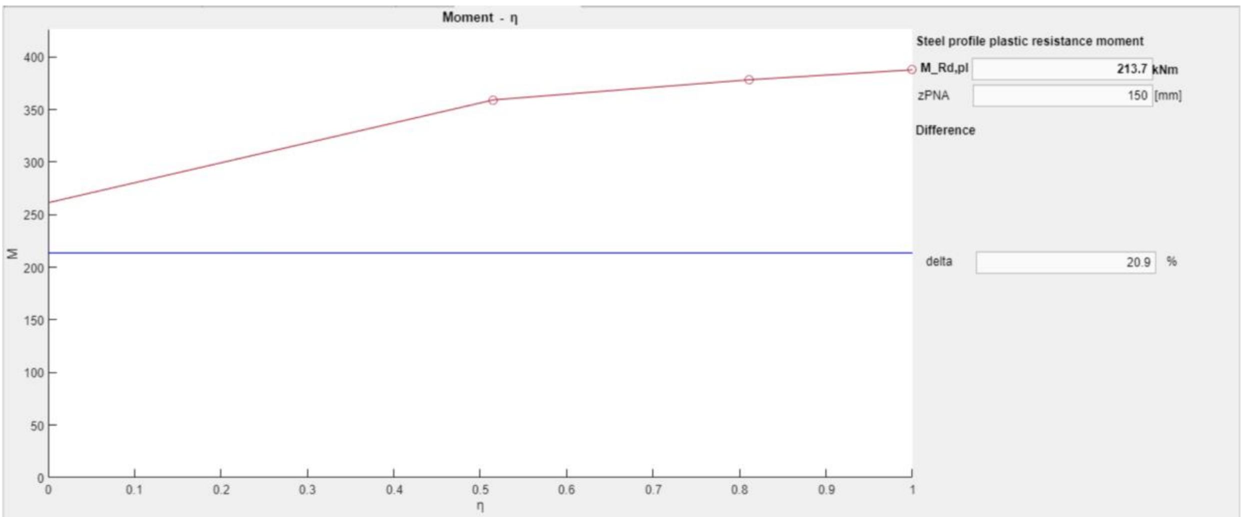
<u>Results for no shear connection:</u>



Results for partial shear connection:

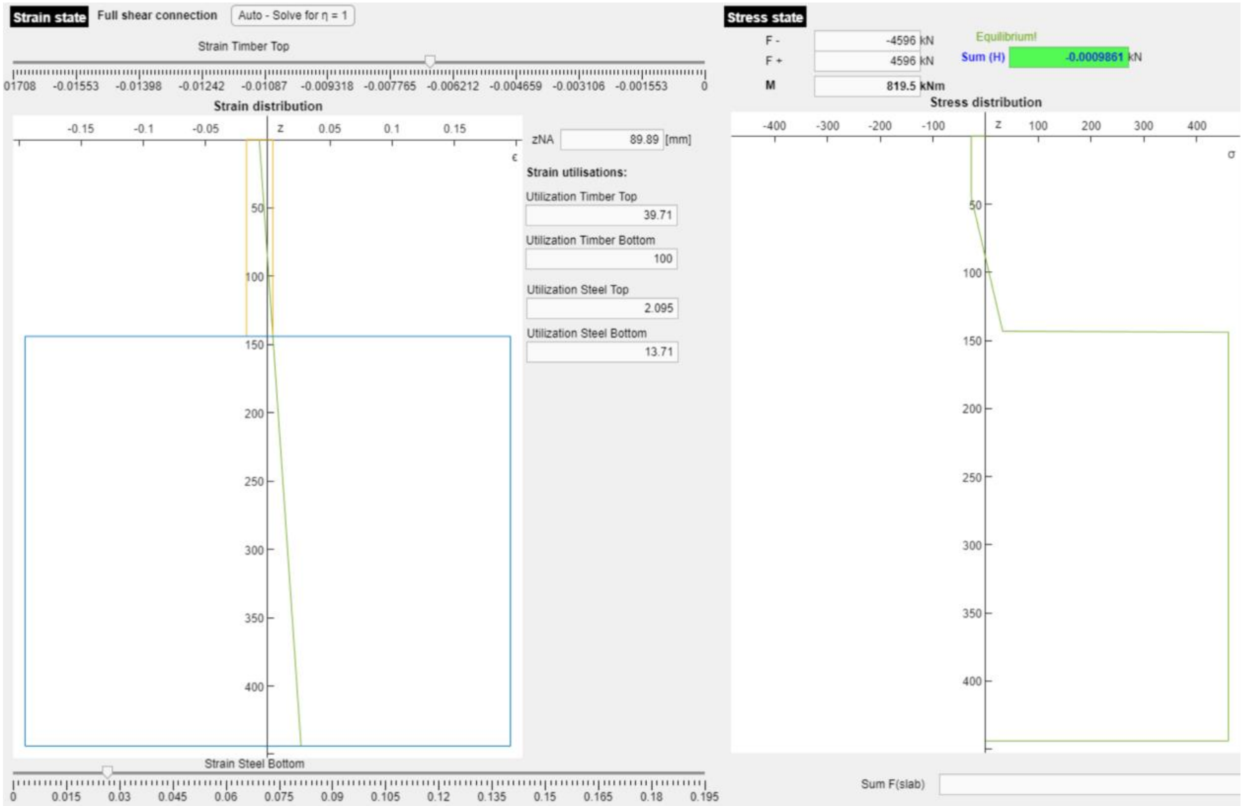


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0138	0.0041	0.0041	0.0756	-1.8418e+03	1.8418e+03	-9.8318e-04	1	387.8231
1	-0.0138	0.0041	0.0150	0.0865	-1.8418e+03	1.8418e+03	-9.8318e-04	1	387.8231
2	-0.0138	0.0041	0.0150	0.0865	-1.8418e+03	1.8418e+03	-9.8318e-04	1	387.8231
3	-0.0138	0.0041	0.0150	0.0865	-1.8418e+03	1.8418e+03	-9.8318e-04	1	387.8231
4	-0.0106	0.0041	-3.8789e-04	0.0581	-1.4940e+03	1.4930e+03	-0.9979	0.8112	378.4045
5	-0.0073	0.0041	-0.0017	0.0439	-949.1490	948.1527	-0.9963	0.5153	359.2600
6	-0.0041	0.0041	-0.0169	0.0158	27.2224	-26.2427	0.9797	-0.0148	258.6448

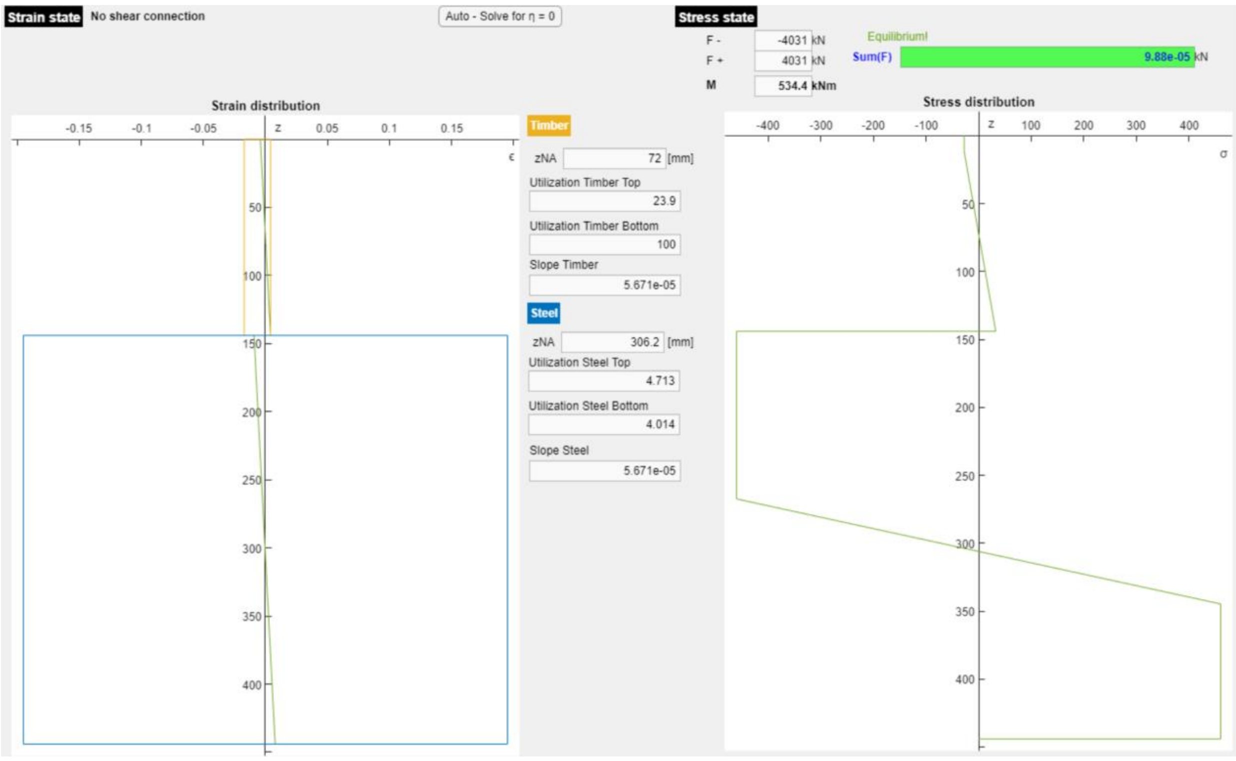


IPE 300, S460, t=2500x144

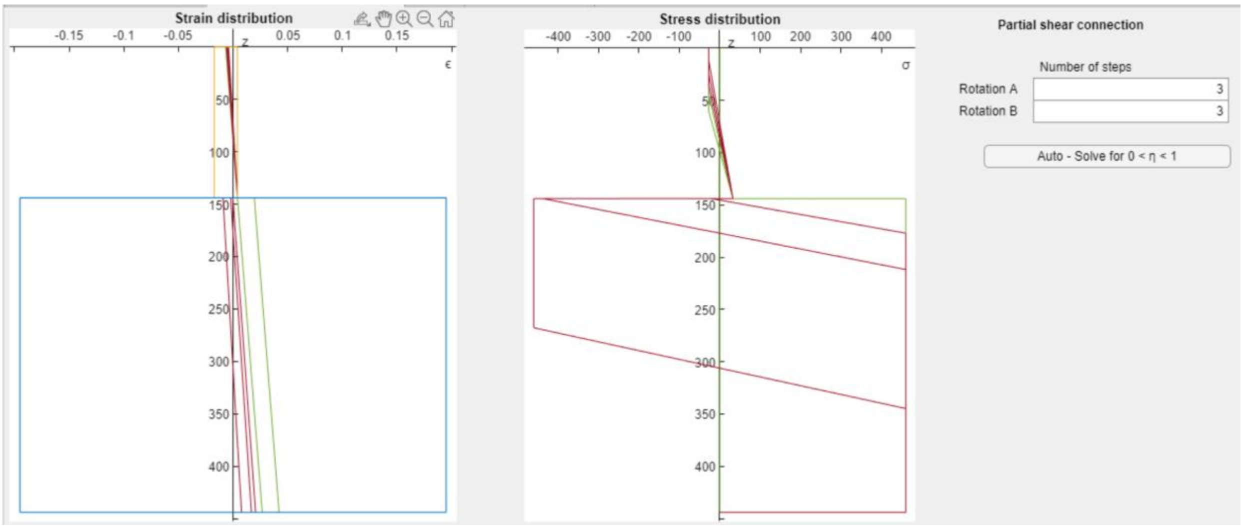
Results for full shear connection:



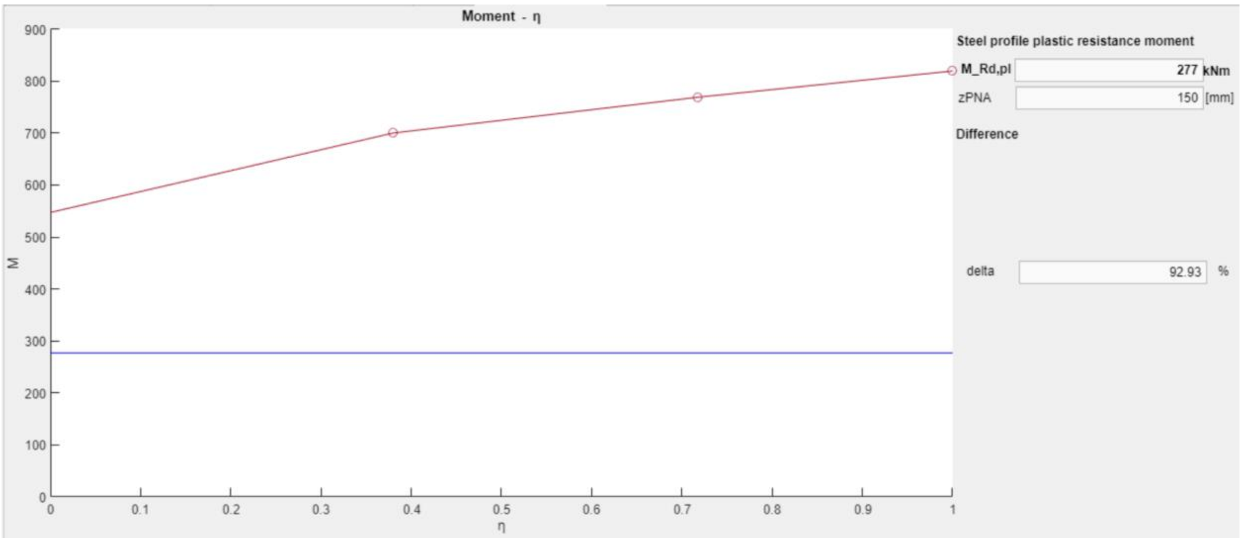
Results for no shear connection:



Results for partial shear connection:

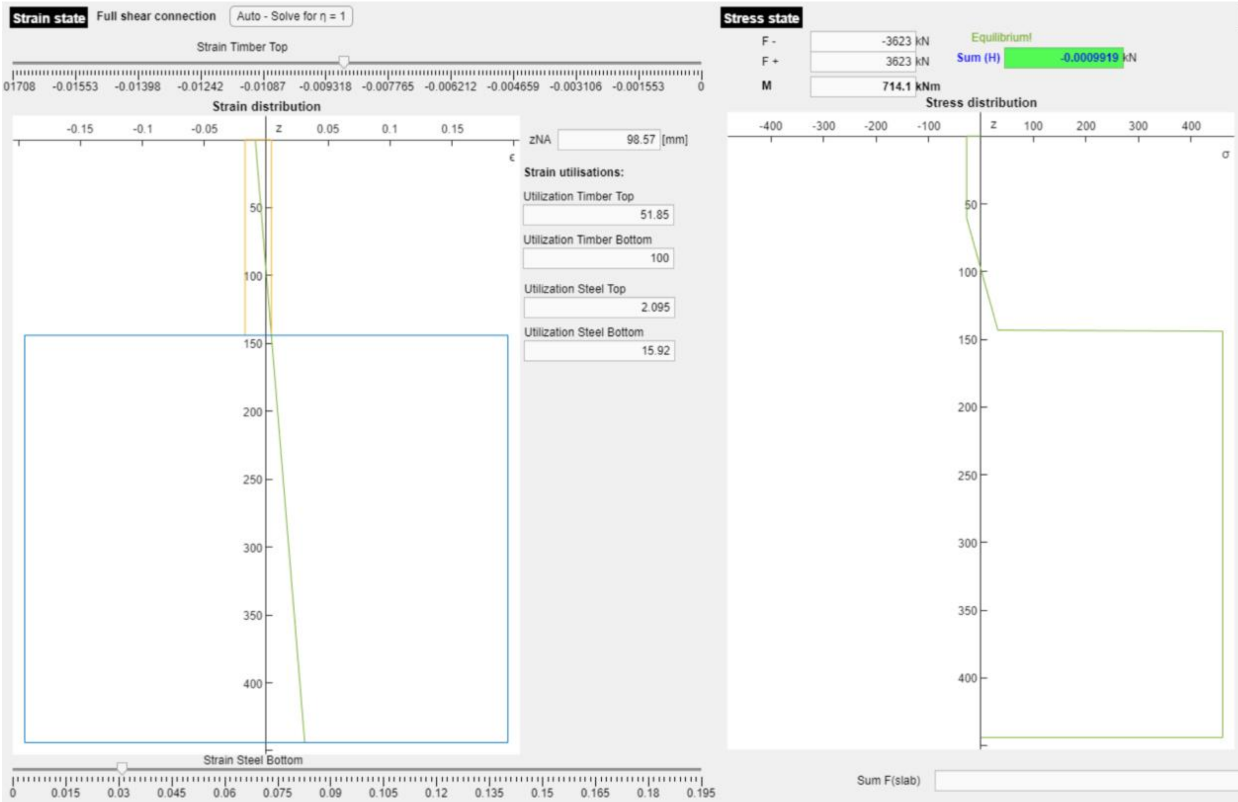


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0068	0.0041	0.0041	0.0267	-2.3865e+03	2.3865e+03	-9.8612e-04	1	819.5395
1	-0.0068	0.0041	0.0195	0.0421	-2.3865e+03	2.3865e+03	-9.8612e-04	1	819.5395
2	-0.0068	0.0041	0.0195	0.0421	-2.3865e+03	2.3865e+03	-9.8612e-04	1	819.5395
3	-0.0068	0.0041	0.0195	0.0421	-2.3865e+03	2.3865e+03	-9.8612e-04	1	819.5395
4	-0.0059	0.0041	-1.0329e-04	0.0207	-1.7132e+03	1.7122e+03	-1.0000	0.7179	769.0521
5	-0.0050	0.0041	-0.0021	0.0168	-906.3388	905.3445	-0.9943	0.3798	700.1173
6	-0.0041	0.0041	-0.0092	0.0078	78.4320	-79.4315	-0.9995	-0.0329	534.0458

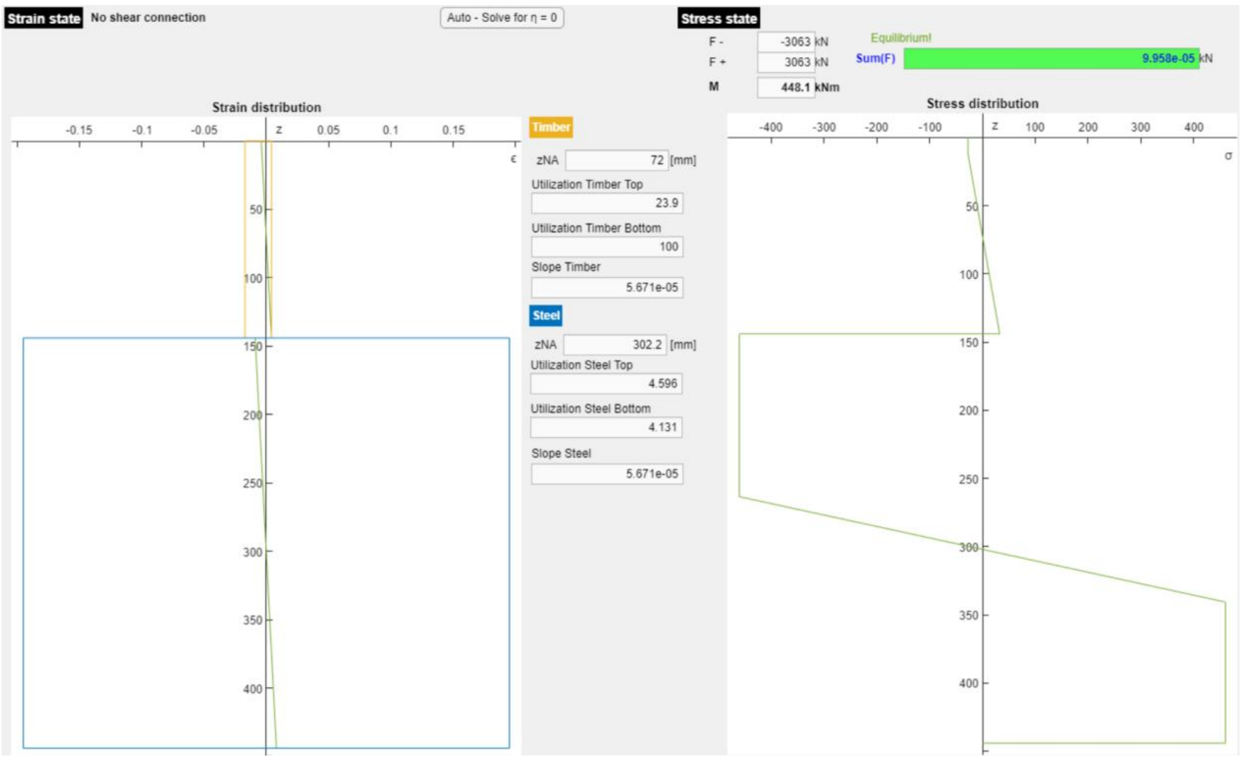


IPE 300, S460, t=1666x144

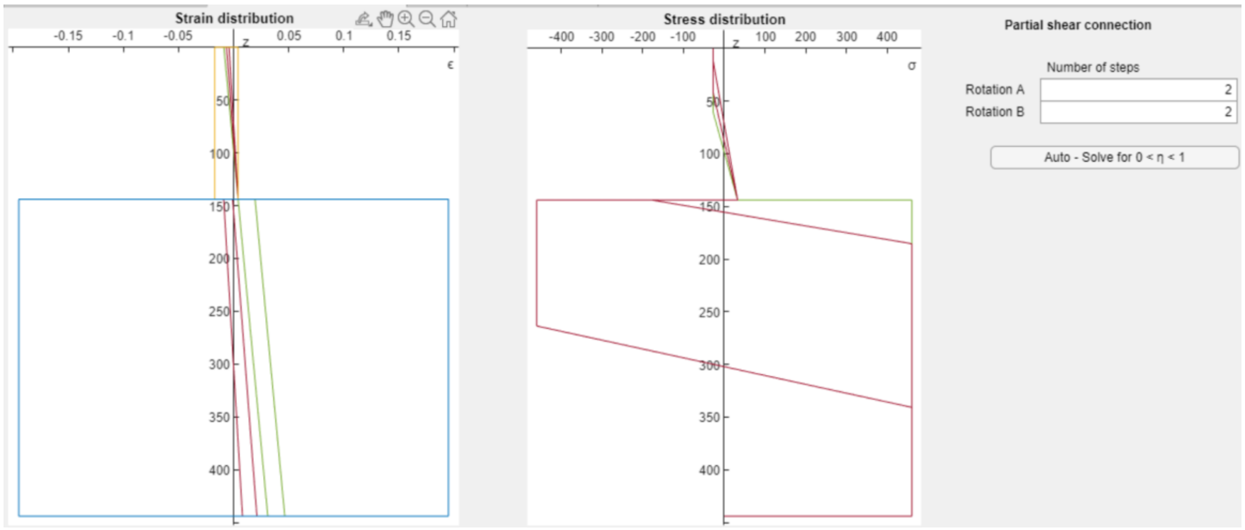
Results for full shear connection:



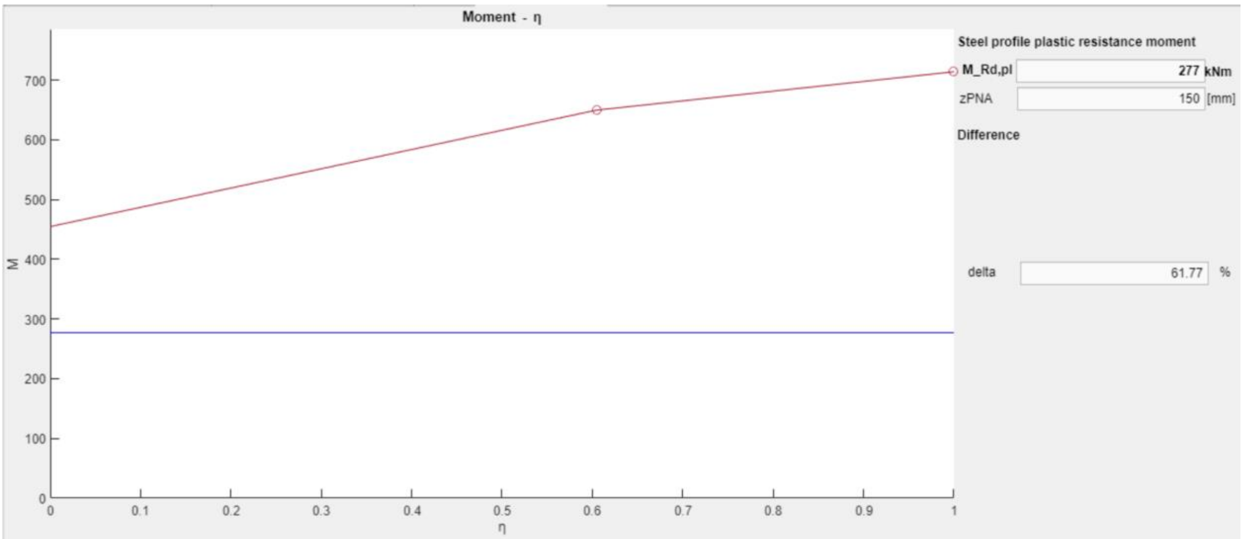
Results for no shear connection:



Results for partial shear connection:

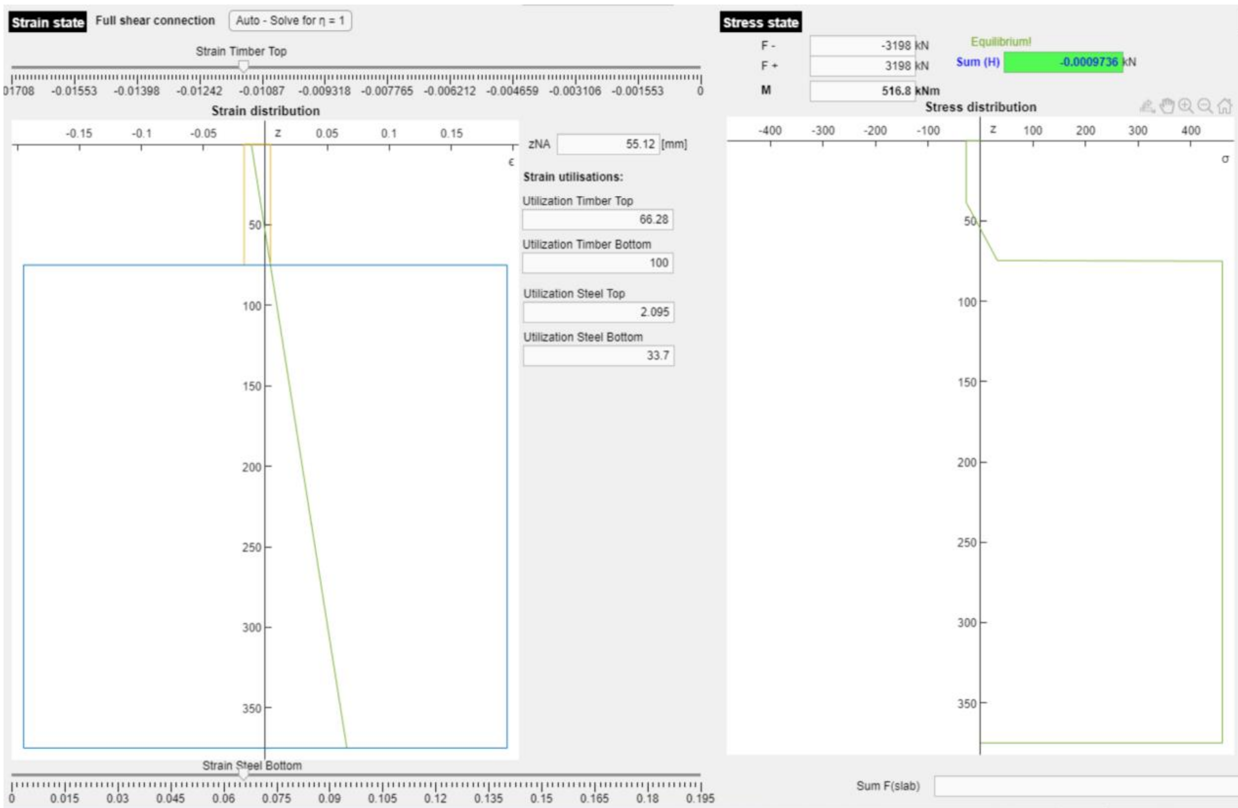


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0089	0.0041	0.0041	0.0310	-2.3865e+03	2.3865e+03	-9.9186e-04	1	714.0809
1	-0.0089	0.0041	0.0195	0.0465	-2.3865e+03	2.3865e+03	-9.9186e-04	1	714.0809
2	-0.0089	0.0041	0.0195	0.0465	-2.3865e+03	2.3865e+03	-9.9186e-04	1	714.0809
3	-0.0065	0.0041	-8.5031e-04	0.0211	-1.4430e+03	1.4420e+03	-0.9982	0.6046	649.8811
4	-0.0041	0.0041	-0.0090	0.0080	52.2671	-53.2529	-0.9858	-0.0219	447.7527

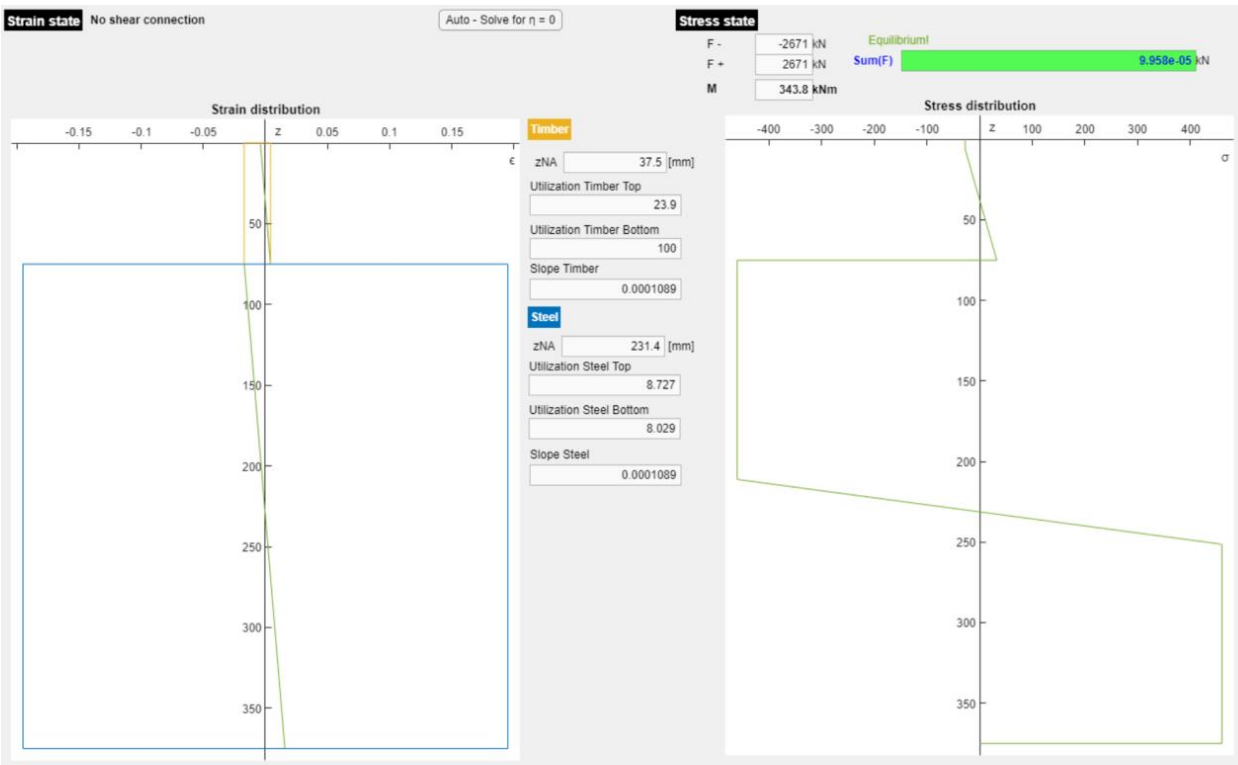


IPE 300, S460, t=2500x75

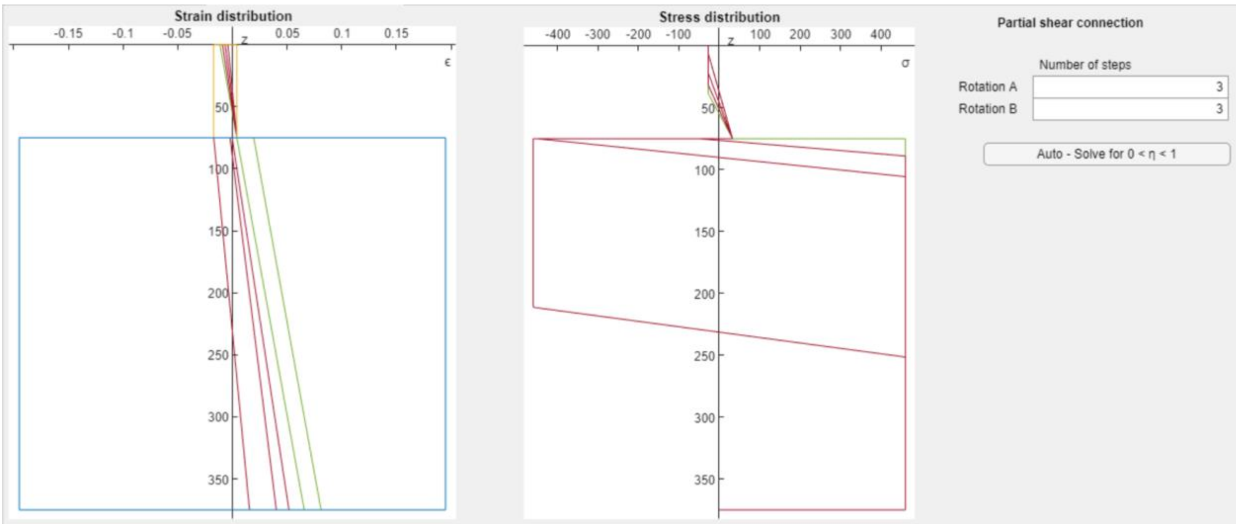
Results for full shear connection:



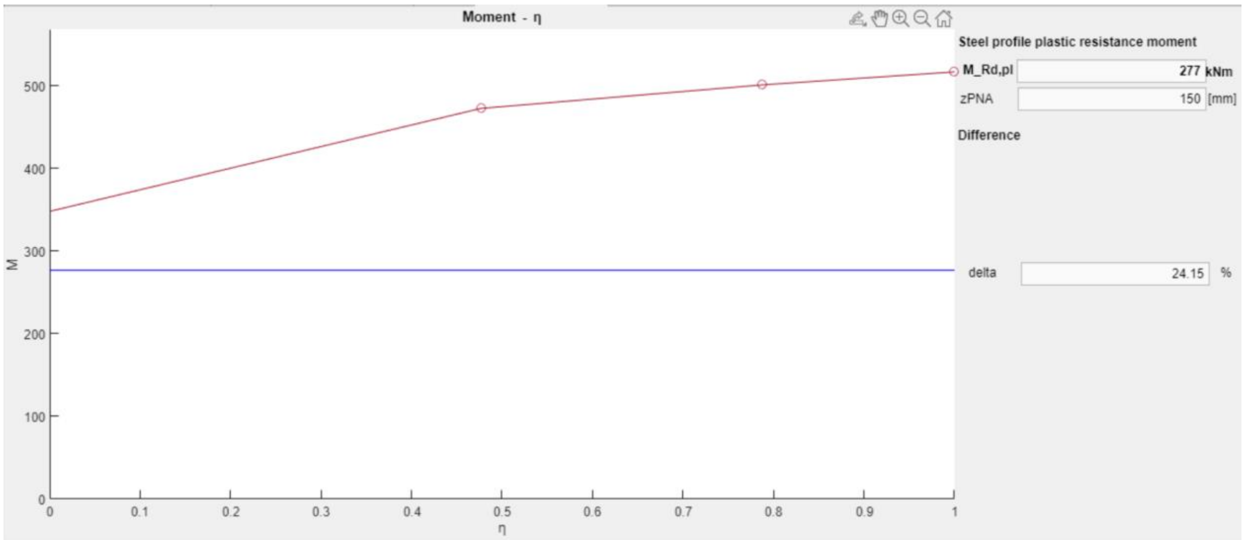
Results for no shear connection:



Results for partial shear connection:

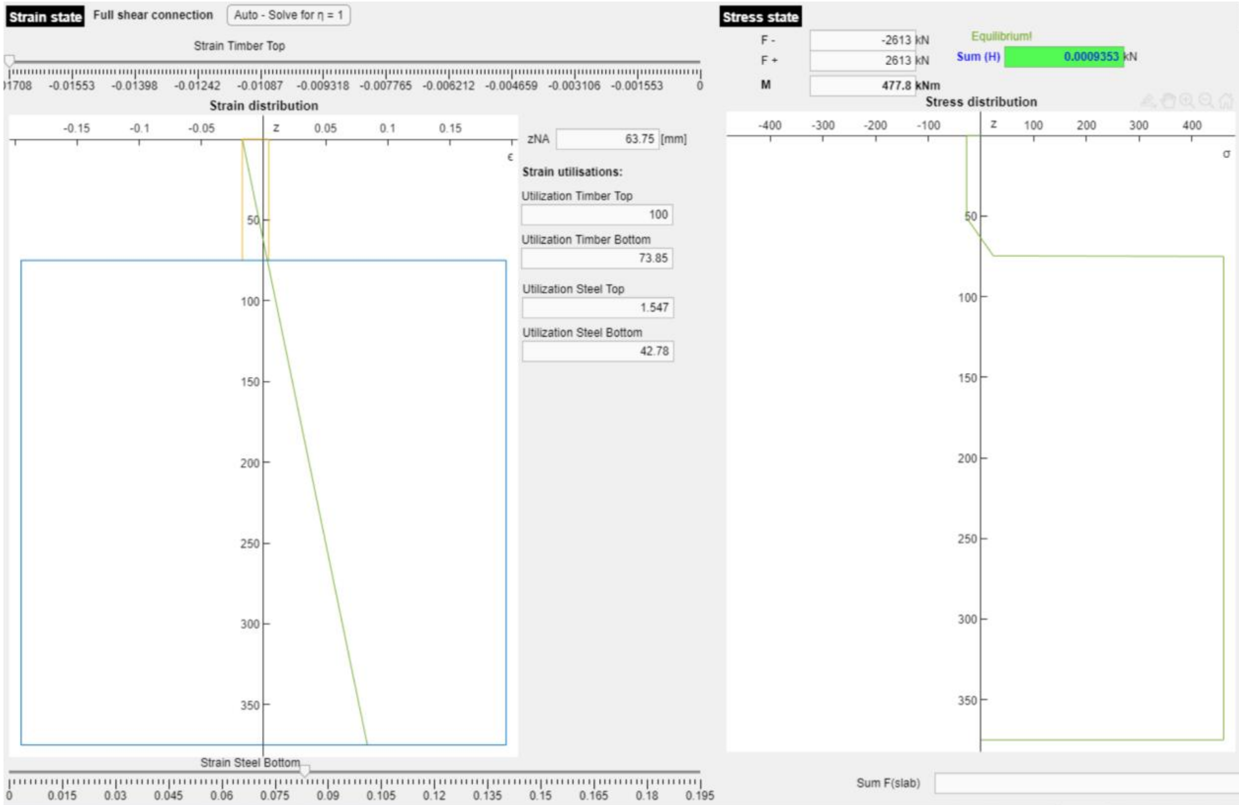


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0113	0.0041	0.0041	0.0657	-2.3865e+03	2.3865e+03	-9.7357e-04	1	516.8304
1	-0.0113	0.0041	0.0195	0.0811	-2.3865e+03	2.3865e+03	-9.7357e-04	1	516.8304
2	-0.0113	0.0041	0.0195	0.0811	-2.3865e+03	2.3865e+03	-9.7357e-04	1	516.8304
3	-0.0113	0.0041	0.0195	0.0811	-2.3865e+03	2.3865e+03	-9.7357e-04	1	516.8304
4	-0.0089	0.0041	-2.4390e-04	0.0517	-1.8779e+03	1.8769e+03	-0.9999	0.7869	501.0471
5	-0.0065	0.0041	-0.0021	0.0402	-1.1374e+03	1.1364e+03	-0.9976	0.4766	472.6708
6	-0.0041	0.0041	-0.0170	0.0156	40.8500	-41.8357	-0.9857	-0.0171	343.6214

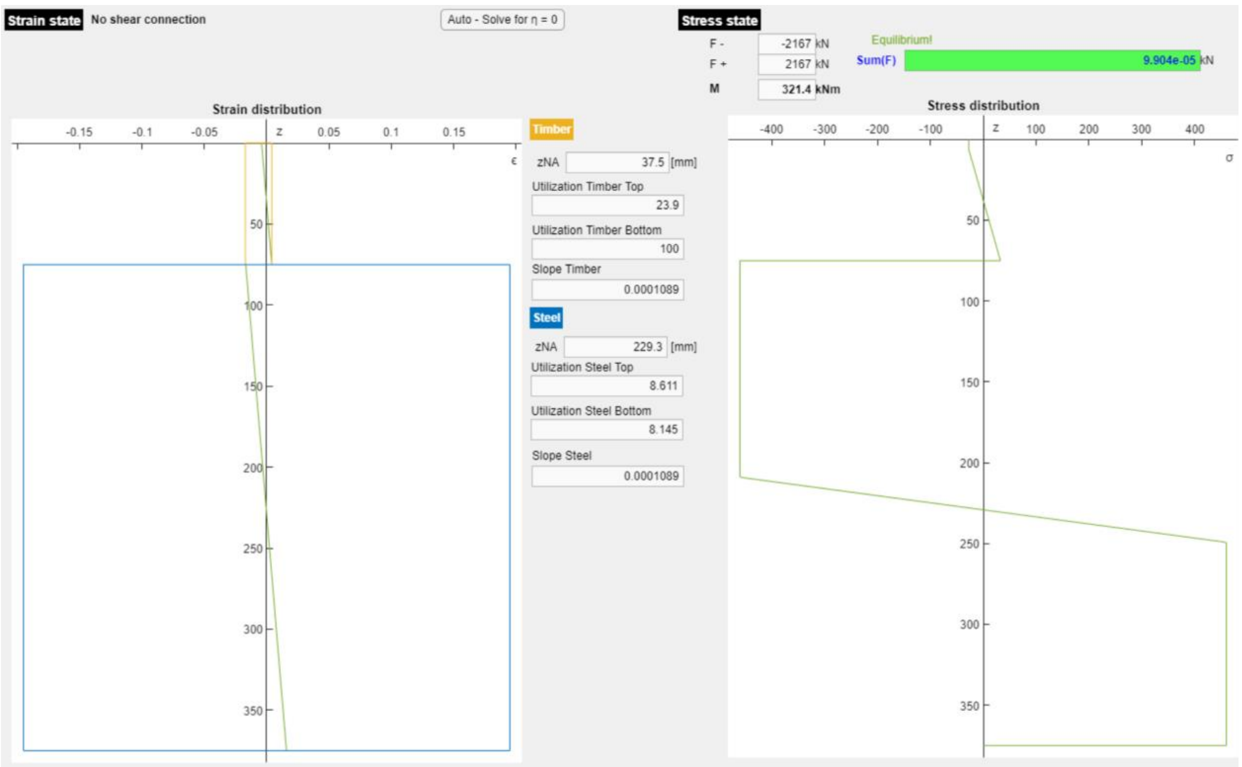


IPE 300, S460, t=1666x75

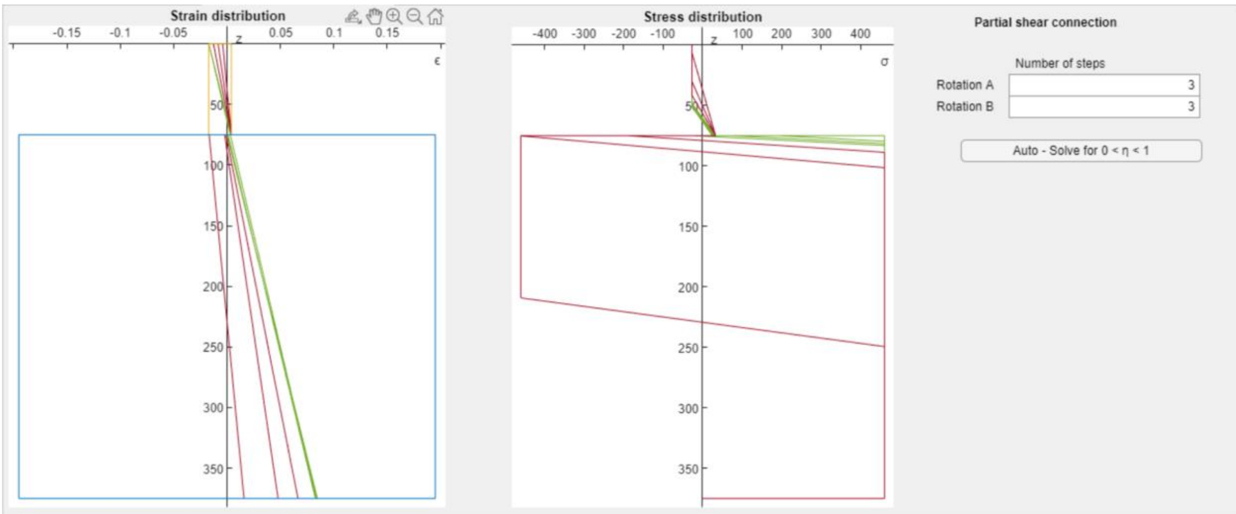
Results for full shear connection:



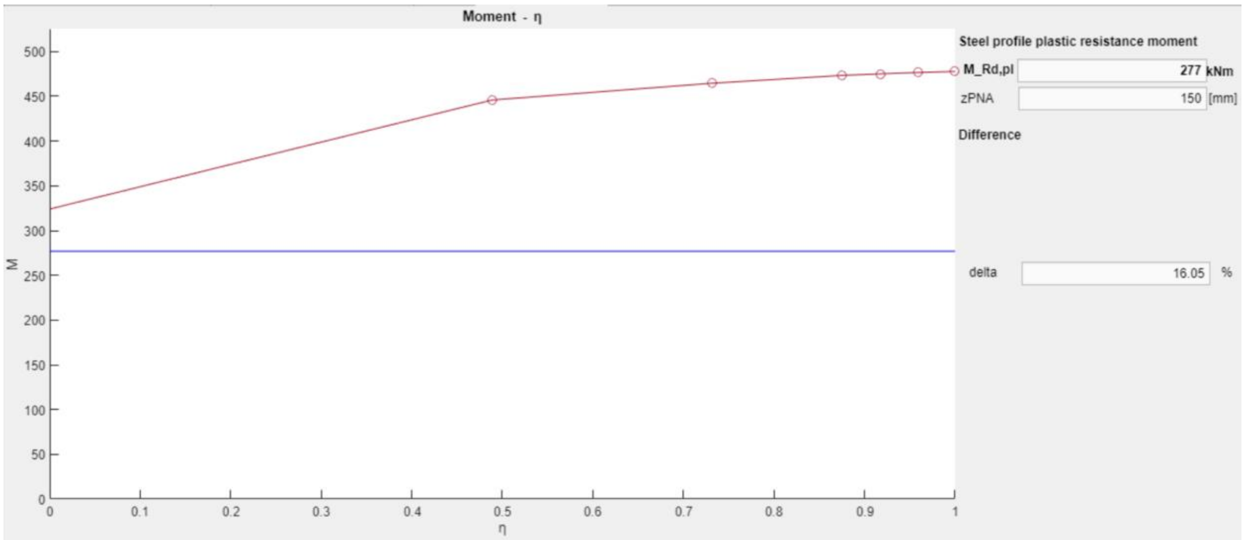
Results for no shear connection:



Results for partial shear connection:

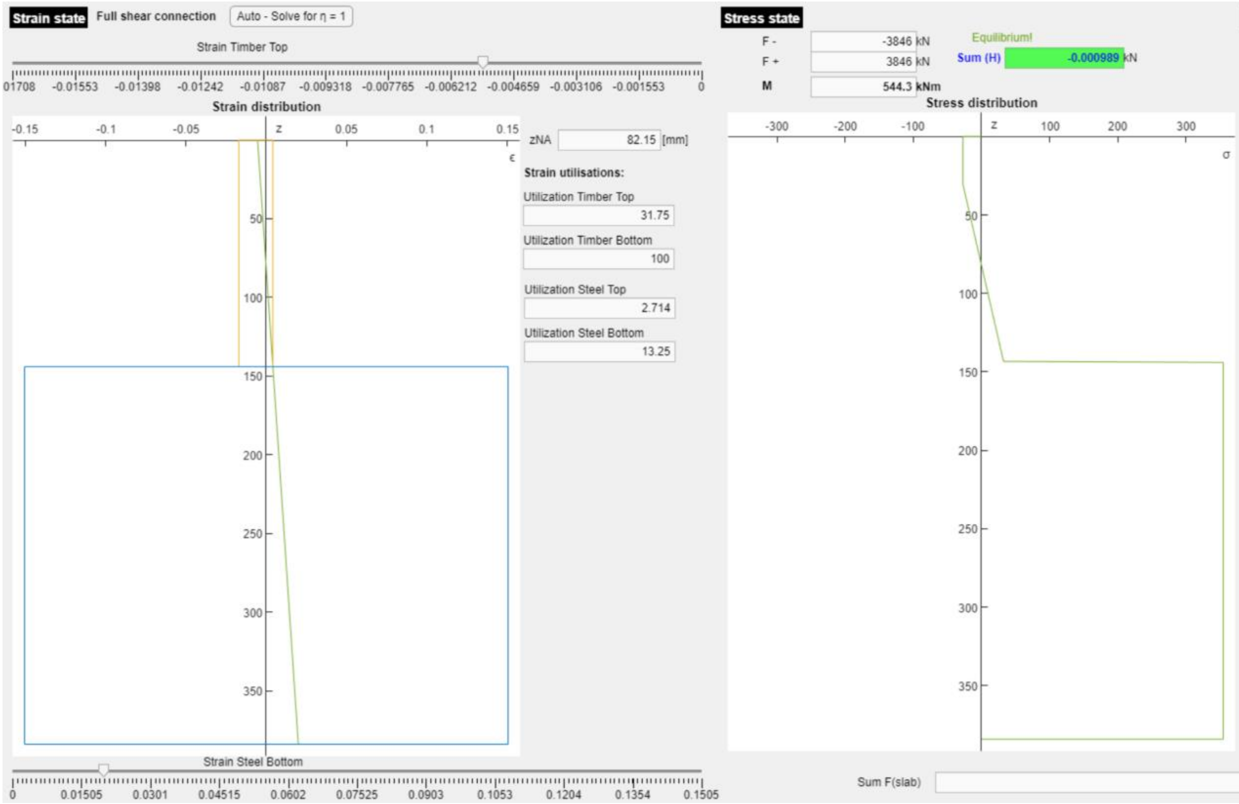


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0171	0.0030	0.0030	0.0834	-2.3865e+03	2.3865e+03	9.3527e-04	1	477.8180
1	-0.0171	0.0034	9.0029e-04	0.0827	-2.2894e+03	2.2904e+03	0.9994	0.9593	476.6296
2	-0.0171	0.0037	3.3245e-04	0.0836	-2.1895e+03	2.1905e+03	0.9990	0.9175	475.1646
3	-0.0171	0.0041	-1.2961e-04	0.0845	-2.0871e+03	2.0861e+03	-0.9997	0.8745	473.3831
4	-0.0128	0.0041	-9.1122e-04	0.0664	-1.7452e+03	1.7442e+03	-0.9946	0.7313	464.6448
5	-0.0084	0.0041	-0.0022	0.0478	-1.1662e+03	1.1652e+03	-0.9848	0.4887	445.9076
6	-0.0041	0.0041	-0.0168	0.0159	27.2224	-28.1993	-0.9768	-0.0114	321.1943

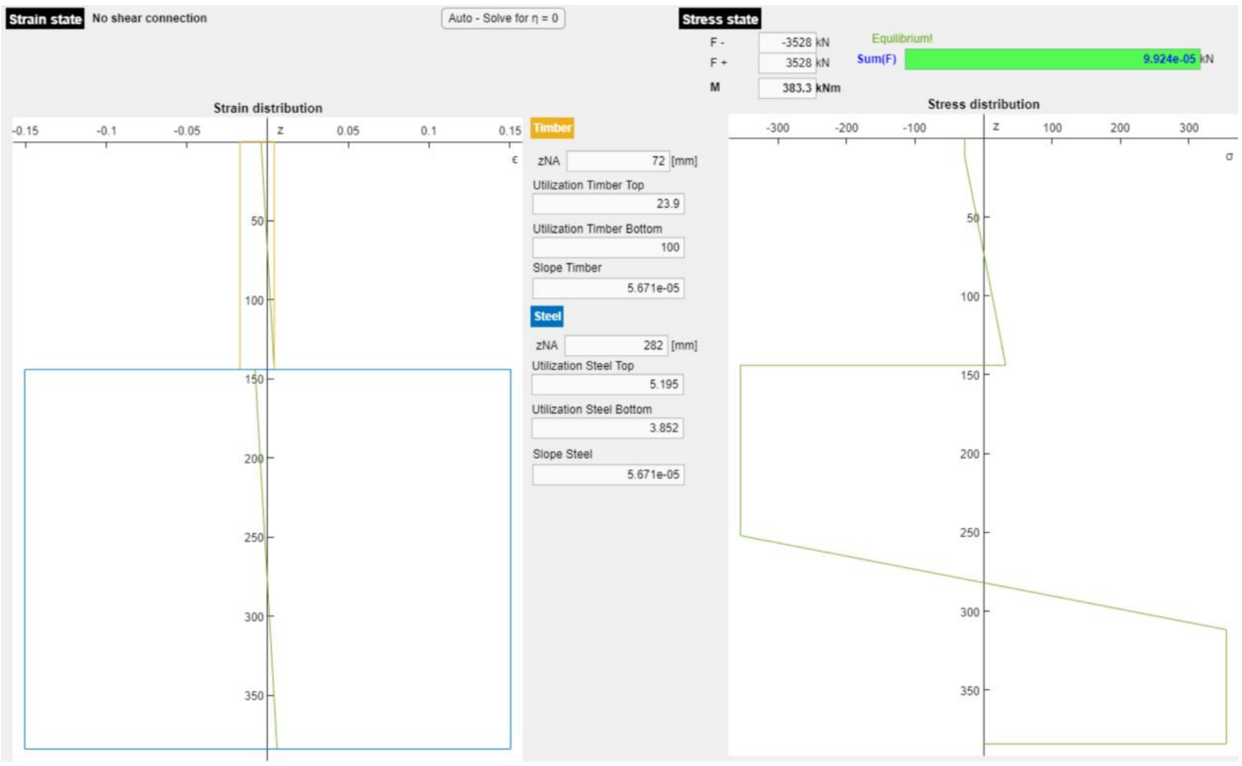


IPE 240, S355, t=2500x144

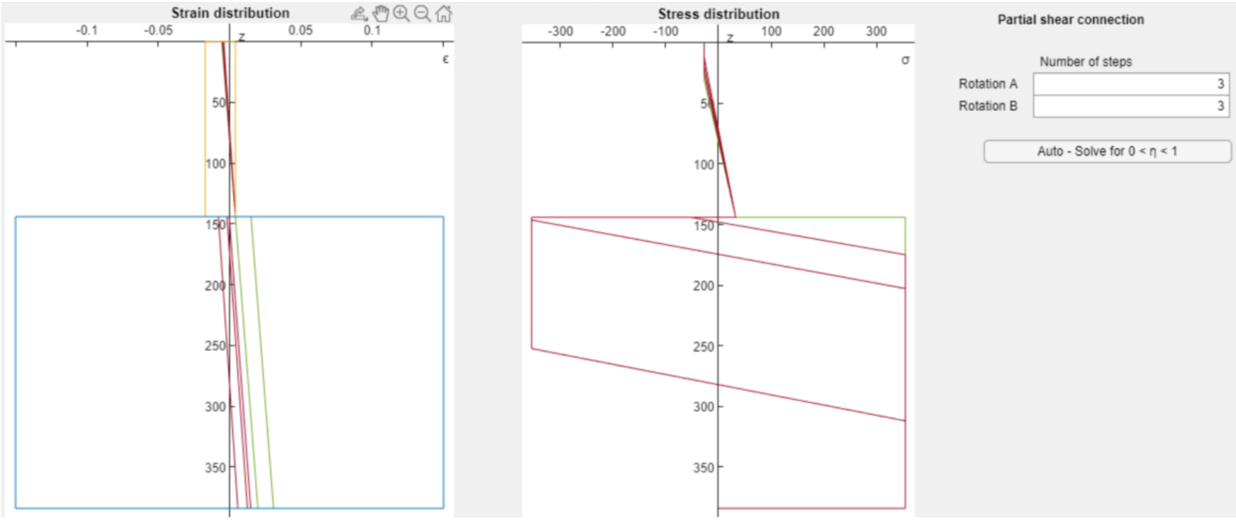
Results for full shear connection:



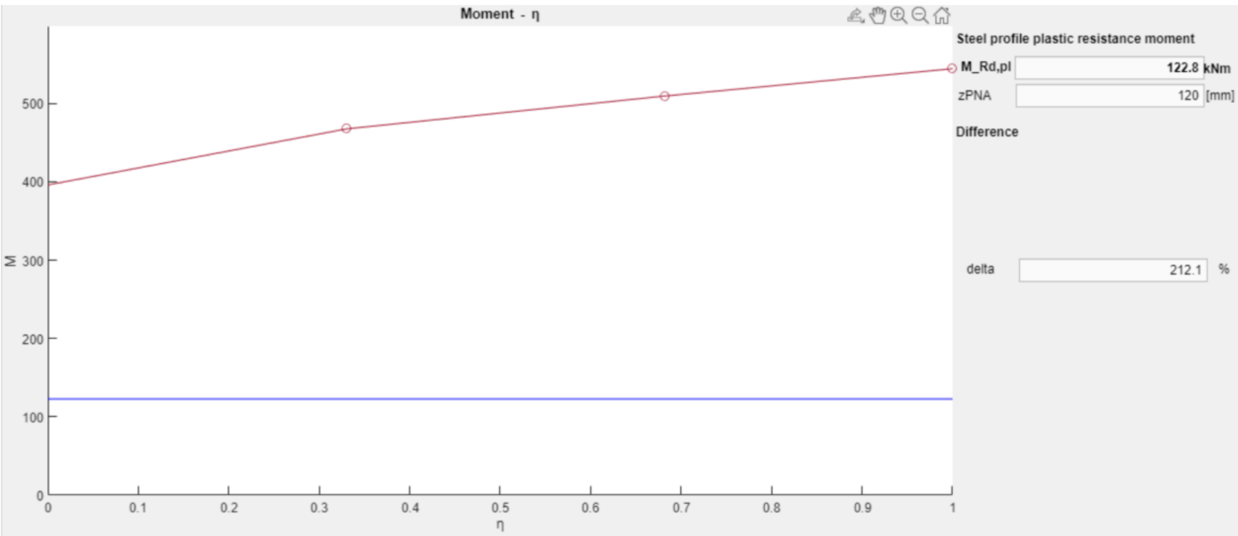
Results for no shear connection:



Results for partial shear connection:

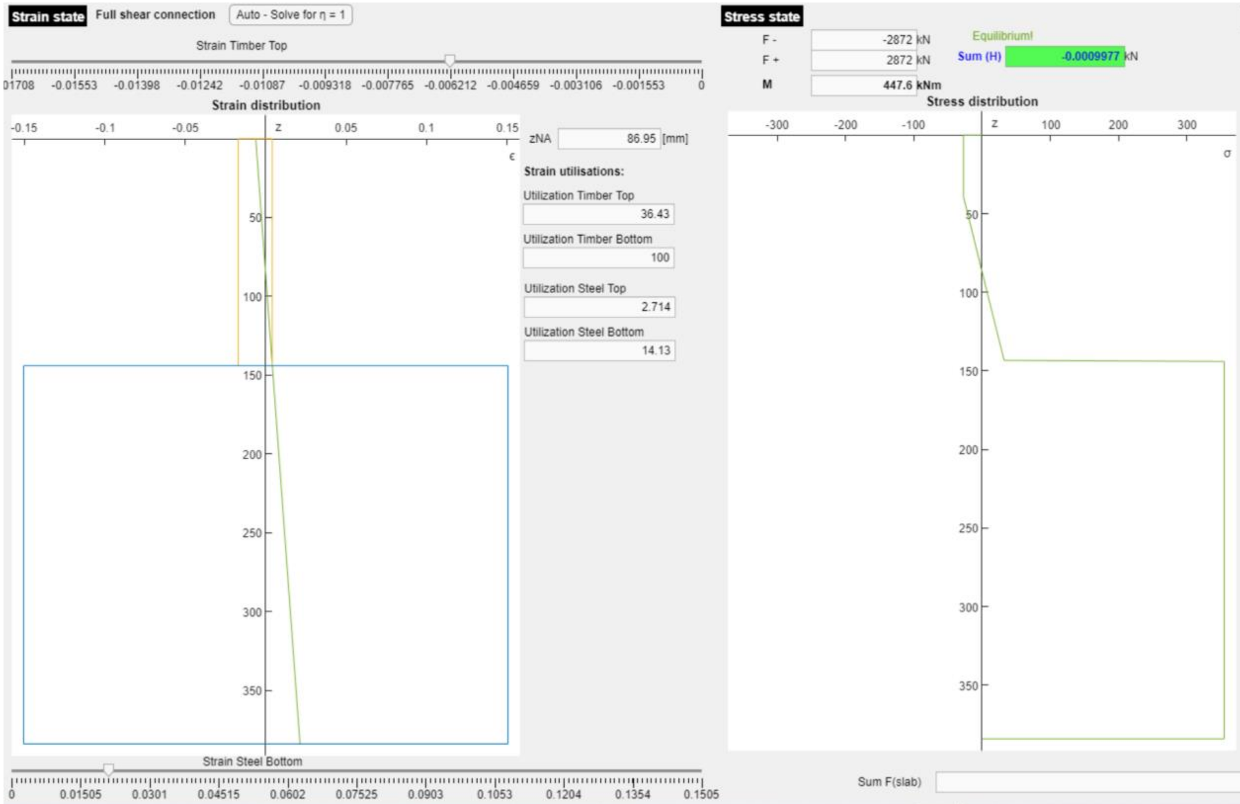


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0054	0.0041	0.0041	0.0199	-1.3201e+03	1.3201e+03	-9.8900e-04	1	544.2585
1	-0.0054	0.0041	0.0150	0.0309	-1.3201e+03	1.3201e+03	-9.8900e-04	1	544.2585
2	-0.0054	0.0041	0.0150	0.0309	-1.3201e+03	1.3201e+03	-9.8900e-04	1	544.2585
3	-0.0054	0.0041	0.0150	0.0309	-1.3201e+03	1.3201e+03	-9.8900e-04	1	544.2585
4	-0.0050	0.0041	-2.4995e-04	0.0149	-899.8580	898.8581	-0.9999	0.6817	509.3500
5	-0.0045	0.0041	-0.0018	0.0125	-436.1226	435.1264	-0.9962	0.3304	467.4876
6	-0.0041	0.0041	-0.0078	0.0058	78.4320	-79.4296	-0.9976	-0.0594	383.0357

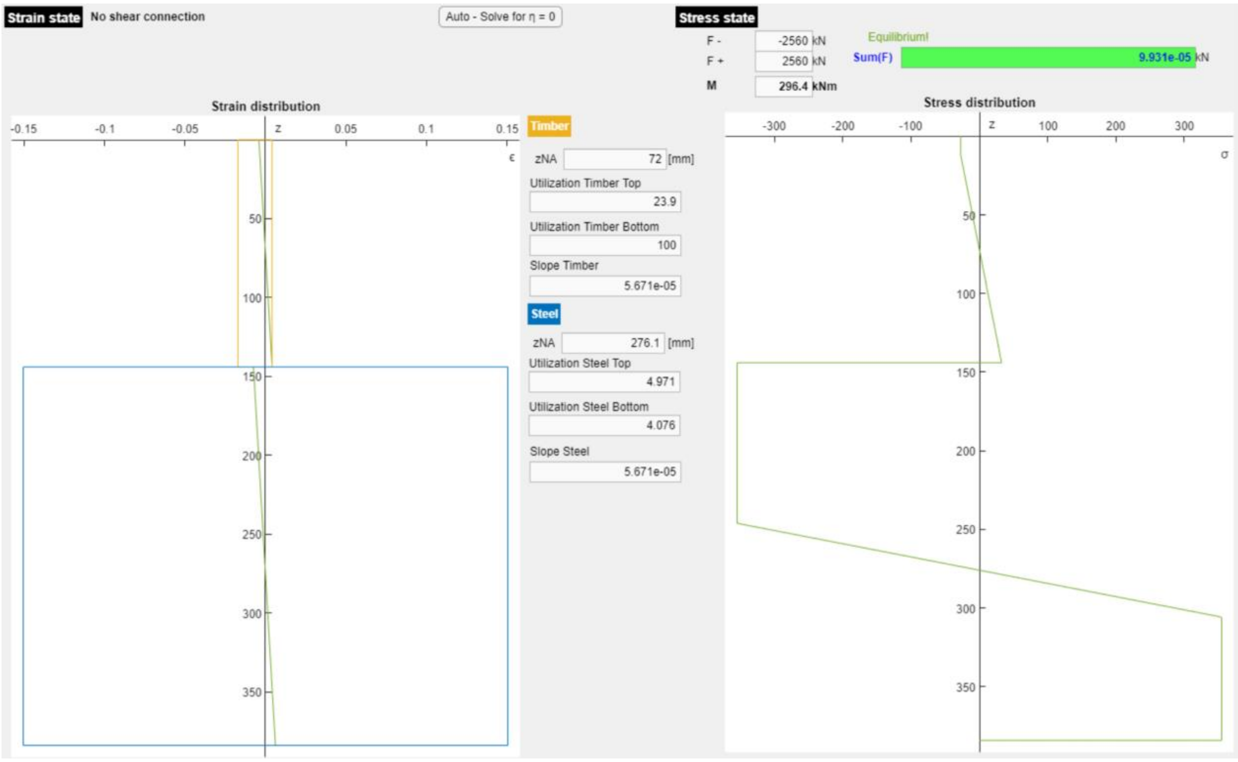


IPE 240, S355, t=1666x144

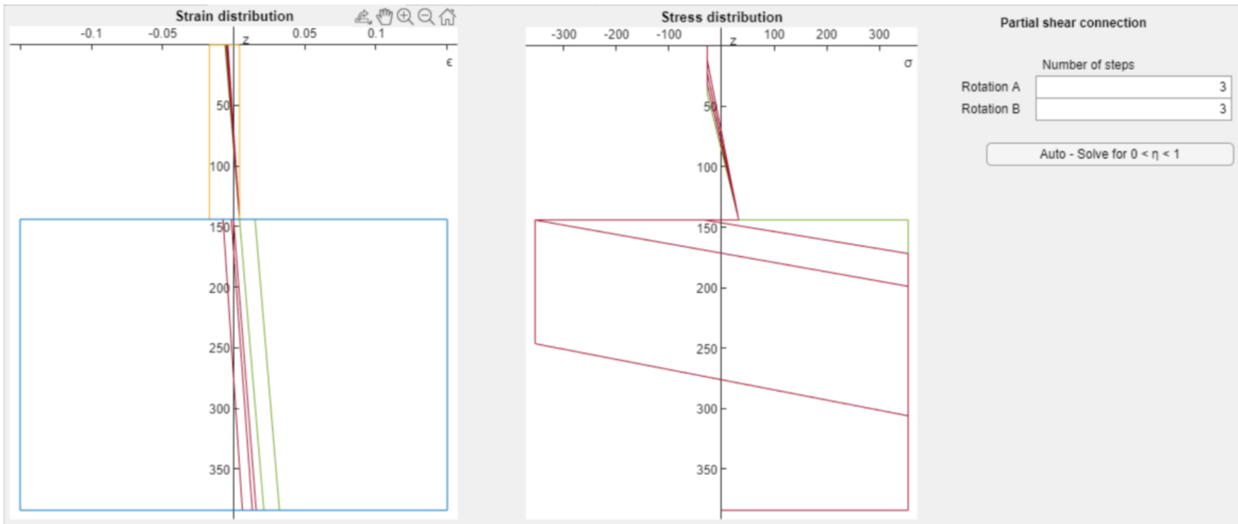
Results for full shear connection:



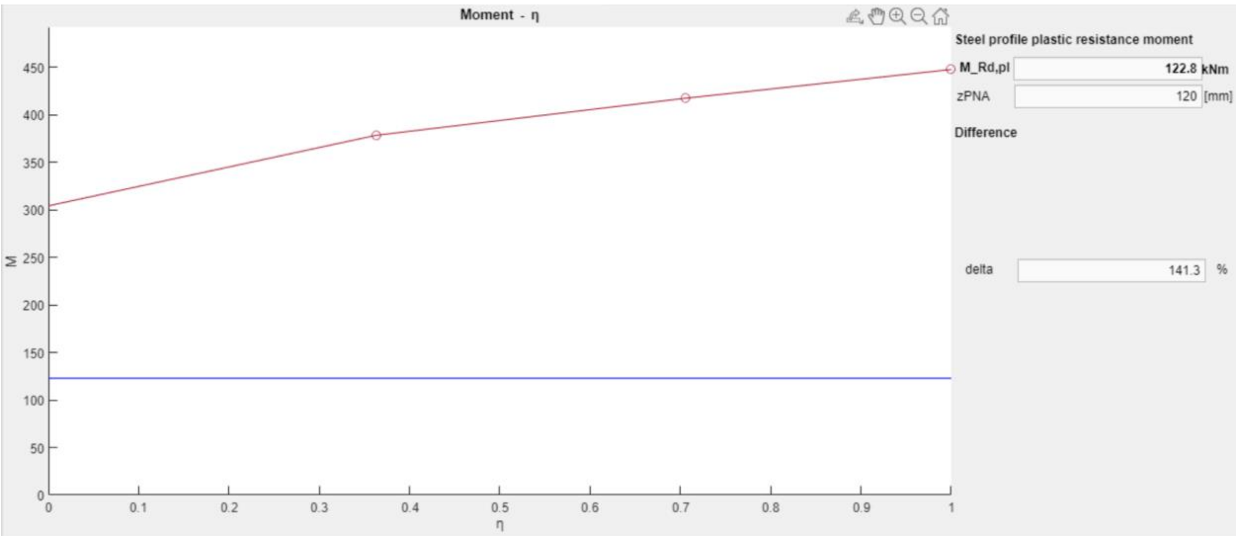
Results for no shear connection:



Results for partial shear connection:

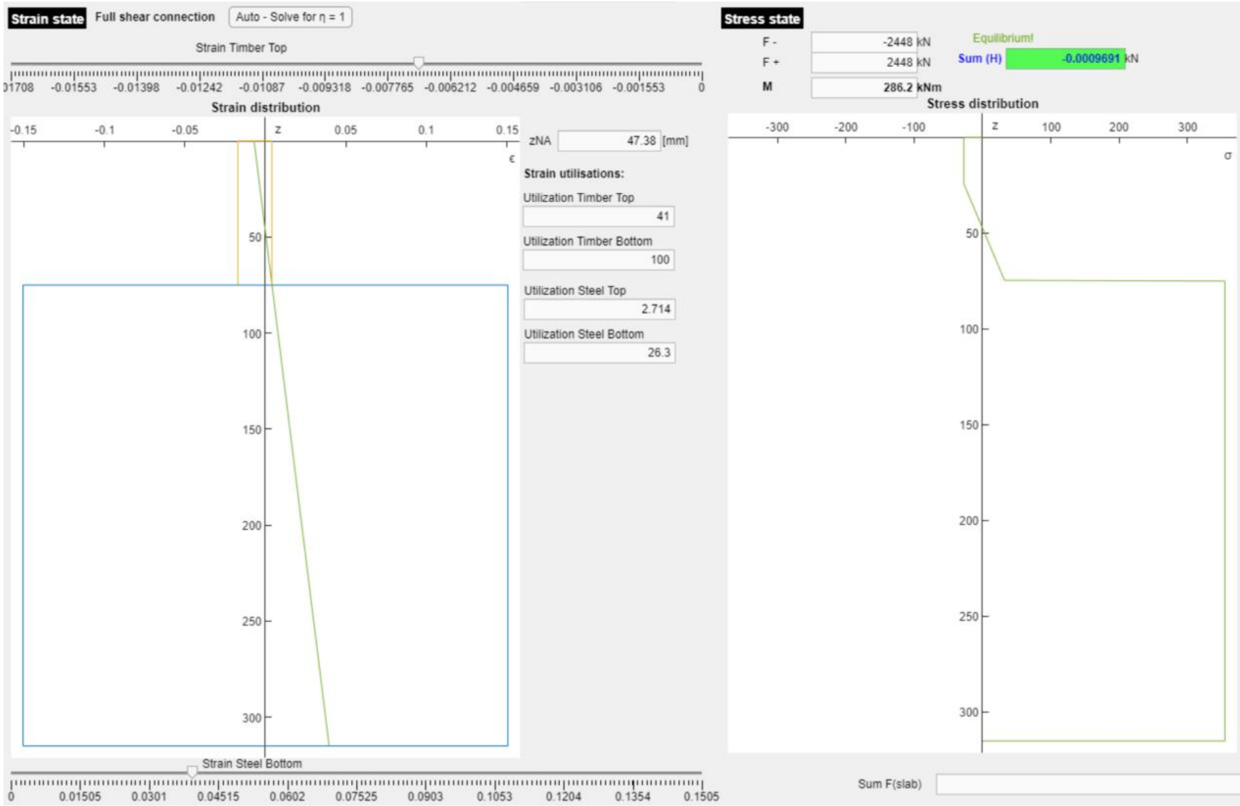


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0062	0.0041	0.0041	0.0213	-1.3201e+03	1.3201e+03	-9.9767e-04	1	447.5950
1	-0.0062	0.0041	0.0150	0.0322	-1.3201e+03	1.3201e+03	-9.9767e-04	1	447.5950
2	-0.0062	0.0041	0.0150	0.0322	-1.3201e+03	1.3201e+03	-9.9767e-04	1	447.5950
3	-0.0062	0.0041	0.0150	0.0322	-1.3201e+03	1.3201e+03	-9.9767e-04	1	447.5950
4	-0.0055	0.0041	-1.6007e-04	0.0158	-930.6490	929.6494	-0.9997	0.7050	417.3020
5.0000	-0.0048	0.0041	-0.0017	0.0131	-478.7018	477.7070	-0.9949	0.3626	378.3265
6.0000	-0.0041	0.0041	-0.0075	0.0061	52.2671	-53.2560	-0.9890	-0.0396	296.0844

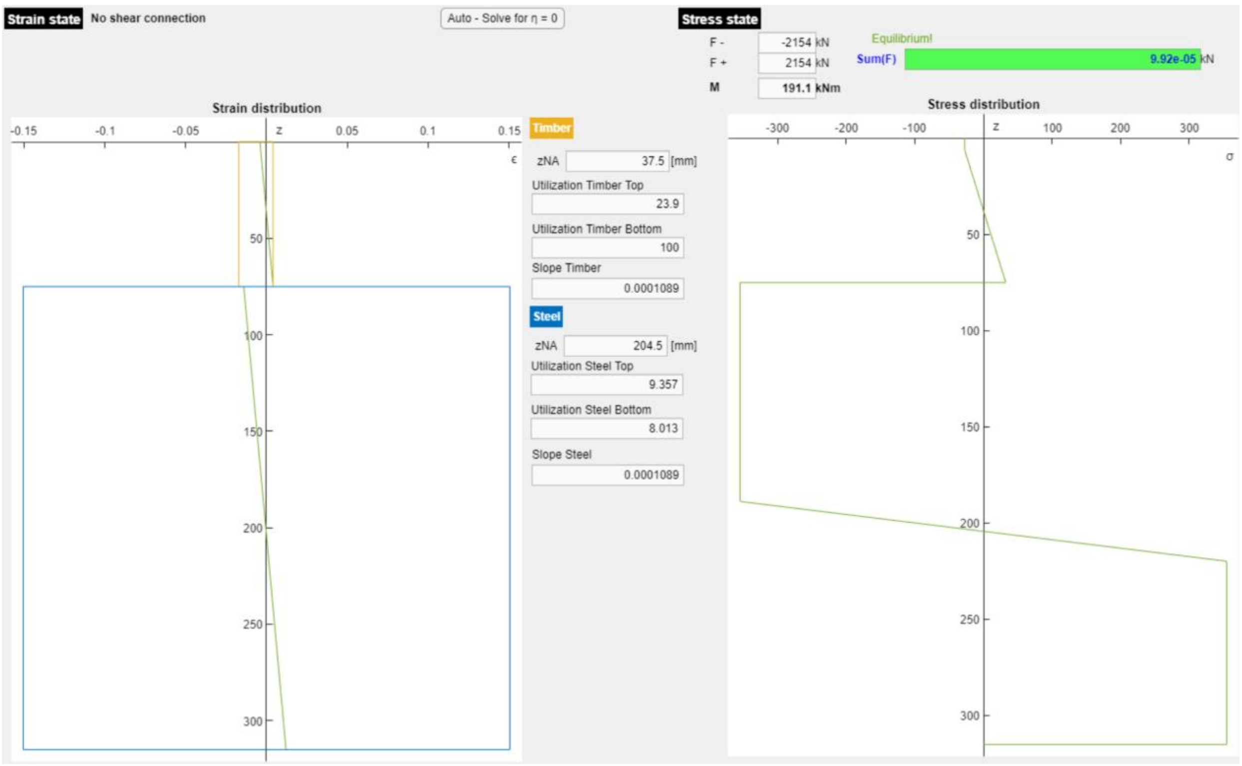


IPE 240, S355, t=2500x75

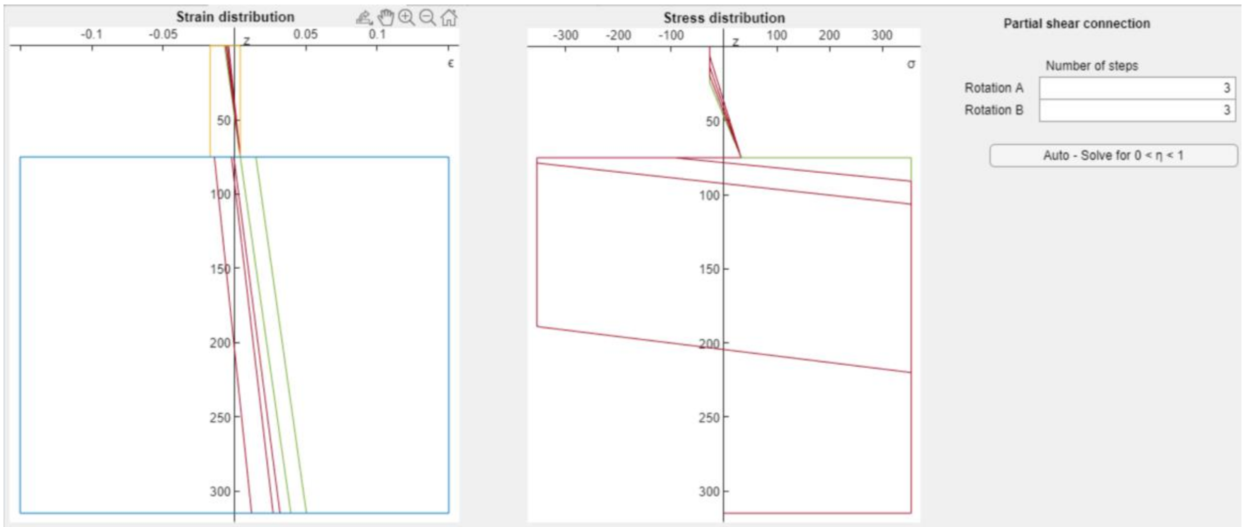
Results for full shear connection:



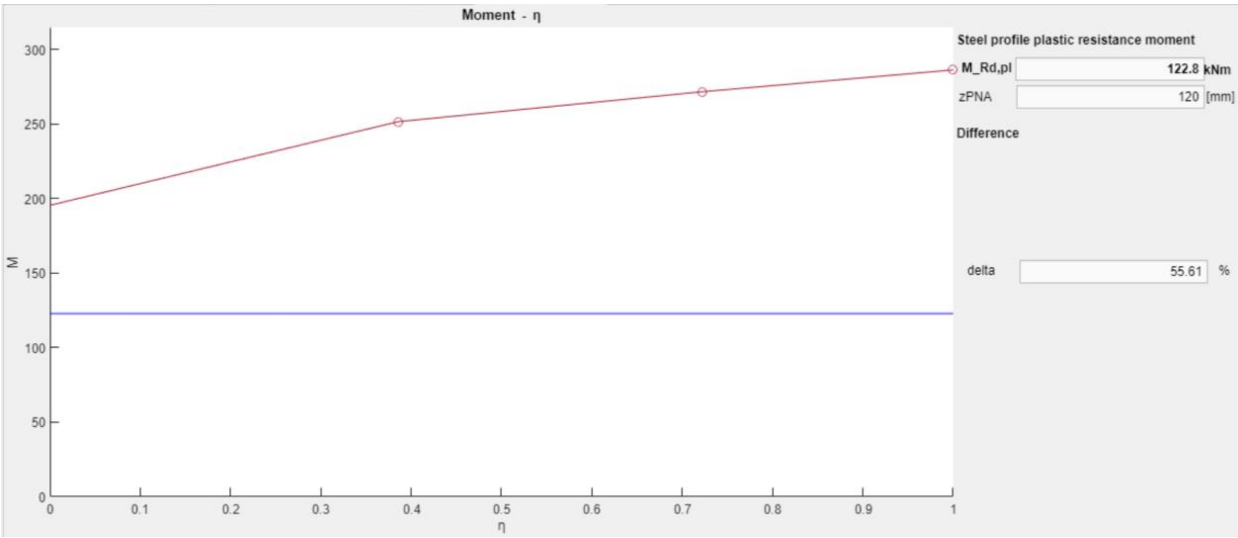
Results for no shear connection:



Results for partial shear connection:

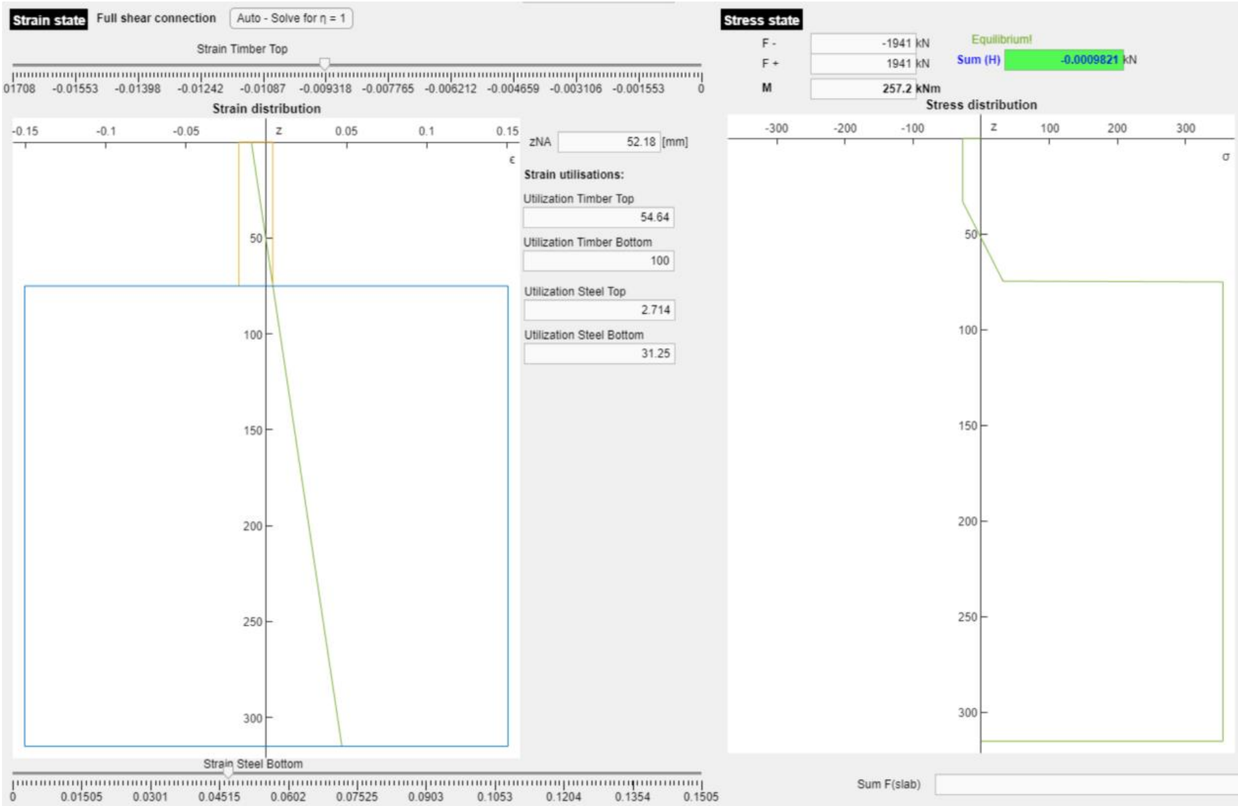


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0070	0.0041	0.0041	0.0396	-1.3201e+03	1.3201e+03	-9.6909e-04	1	286.2473
1	-0.0070	0.0041	0.0150	0.0505	-1.3201e+03	1.3201e+03	-9.6909e-04	1	286.2473
2	-0.0070	0.0041	0.0150	0.0505	-1.3201e+03	1.3201e+03	-9.6909e-04	1	286.2473
3	-0.0070	0.0041	0.0150	0.0505	-1.3201e+03	1.3201e+03	-9.6909e-04	1	286.2473
4	-0.0060	0.0041	-4.4461e-04	0.0319	-953.7669	952.7670	-0.9999	0.7225	271.6319
5	-0.0051	0.0041	-0.0021	0.0271	-509.4551	508.4617	-0.9935	0.3859	251.5868
6	-0.0041	0.0041	-0.0141	0.0120	40.8500	-41.8471	-0.9971	-0.0309	190.9409

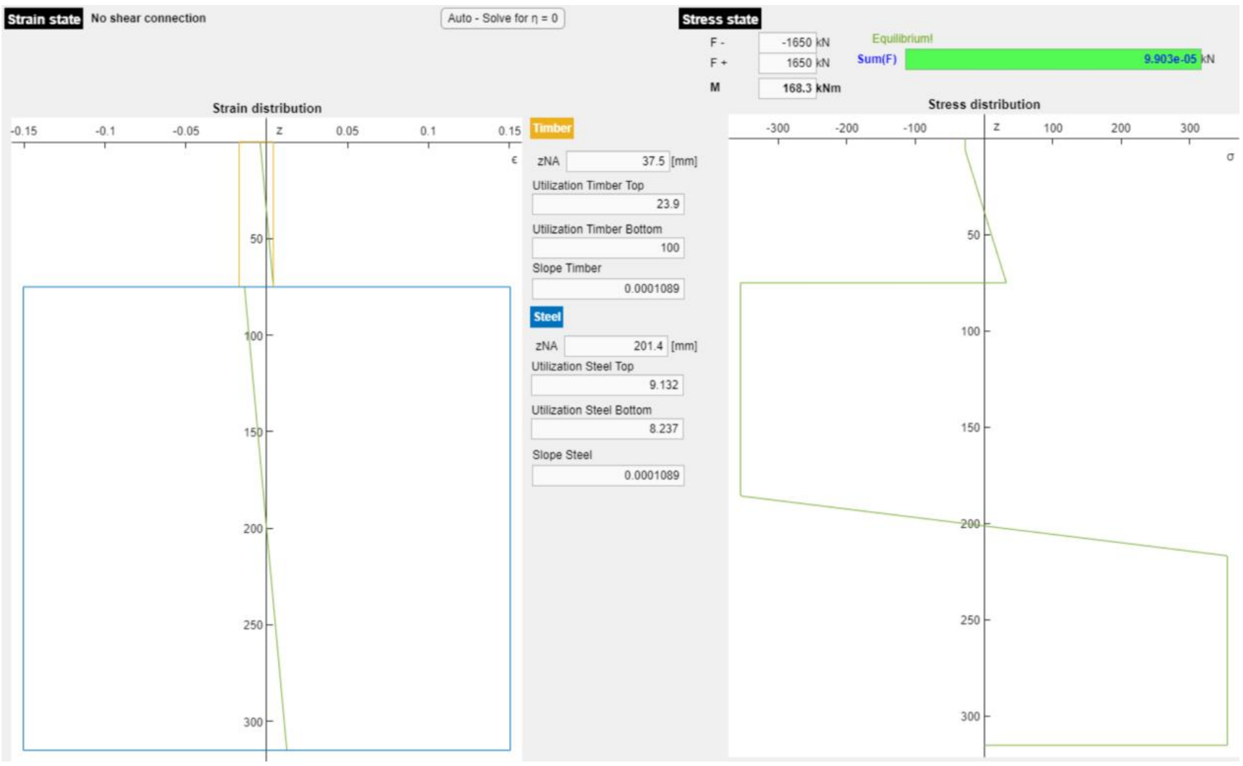


IPE 240, S355, t=1666x75

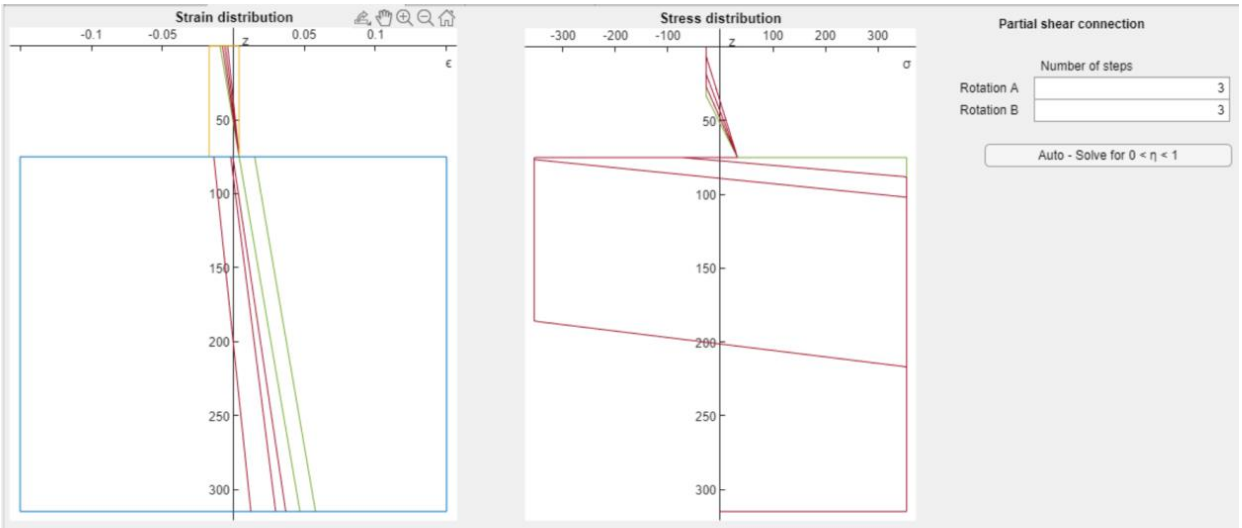
Results for full shear connection:



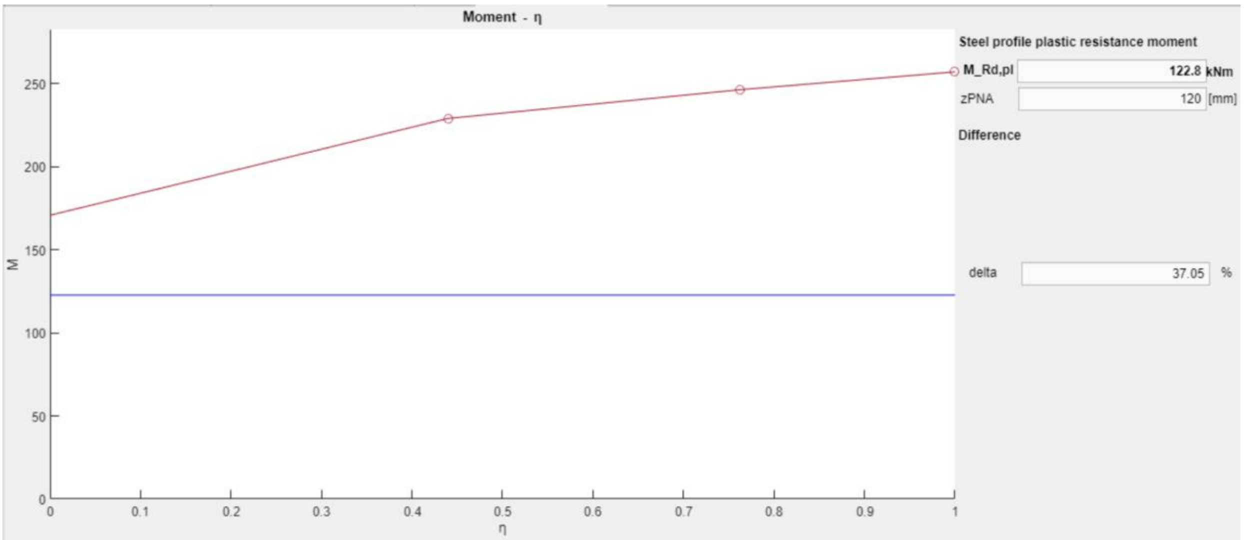
Results for no shear connection:



Results for partial shear connection:

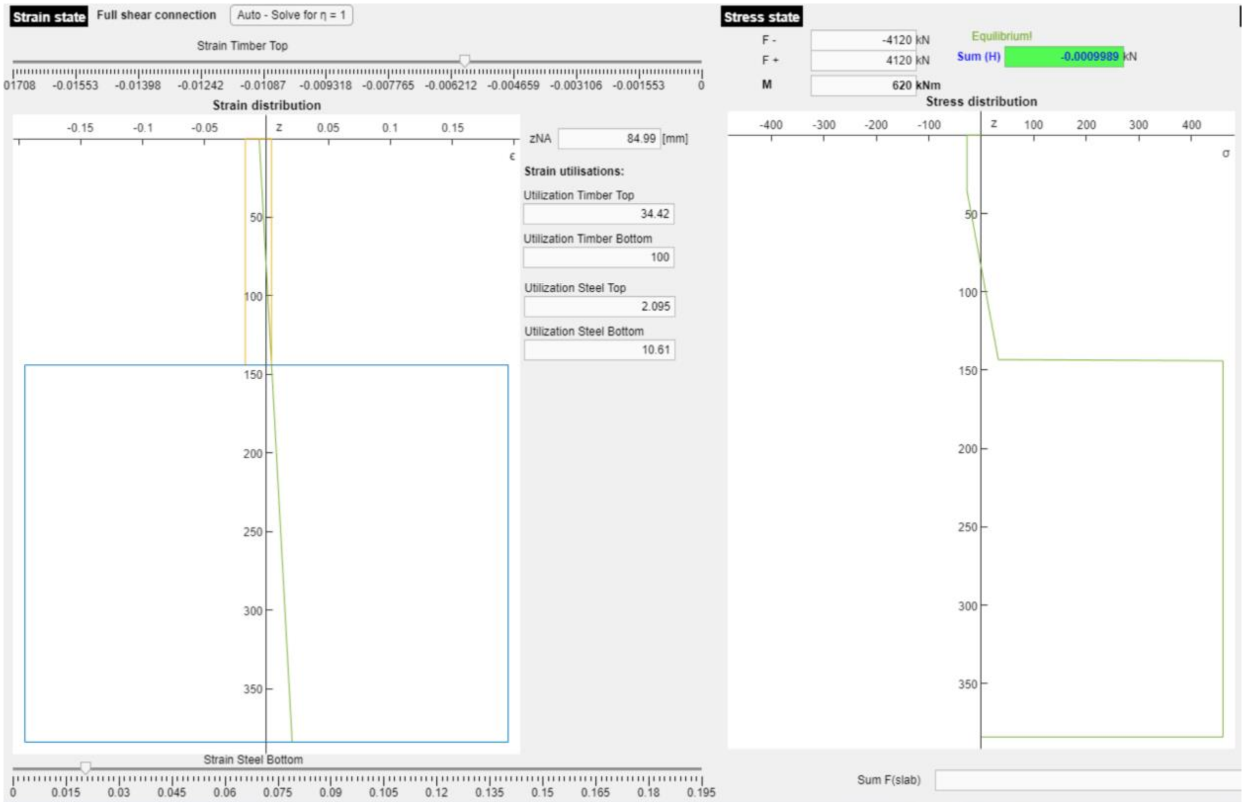


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0093	0.0041	0.0041	0.0470	-1.3201e+03	1.3201e+03	-9.8206e-04	1	257.2007
1	-0.0093	0.0041	0.0150	0.0580	-1.3201e+03	1.3201e+03	-9.8206e-04	1	257.2007
2	-0.0093	0.0041	0.0150	0.0580	-1.3201e+03	1.3201e+03	-9.8206e-04	1	257.2007
3	-0.0093	0.0041	0.0150	0.0580	-1.3201e+03	1.3201e+03	-9.8206e-04	1	257.2007
4	-0.0076	0.0041	-3.4430e-04	0.0370	-1.0057e+03	1.0047e+03	-0.9994	0.7619	246.4368
5	-0.0058	0.0041	-0.0019	0.0299	-580.4133	579.4144	-0.9989	0.4397	229.1577
6	-0.0041	0.0041	-0.0138	0.0124	27.2224	-28.2101	-0.9876	-0.0206	168.1402

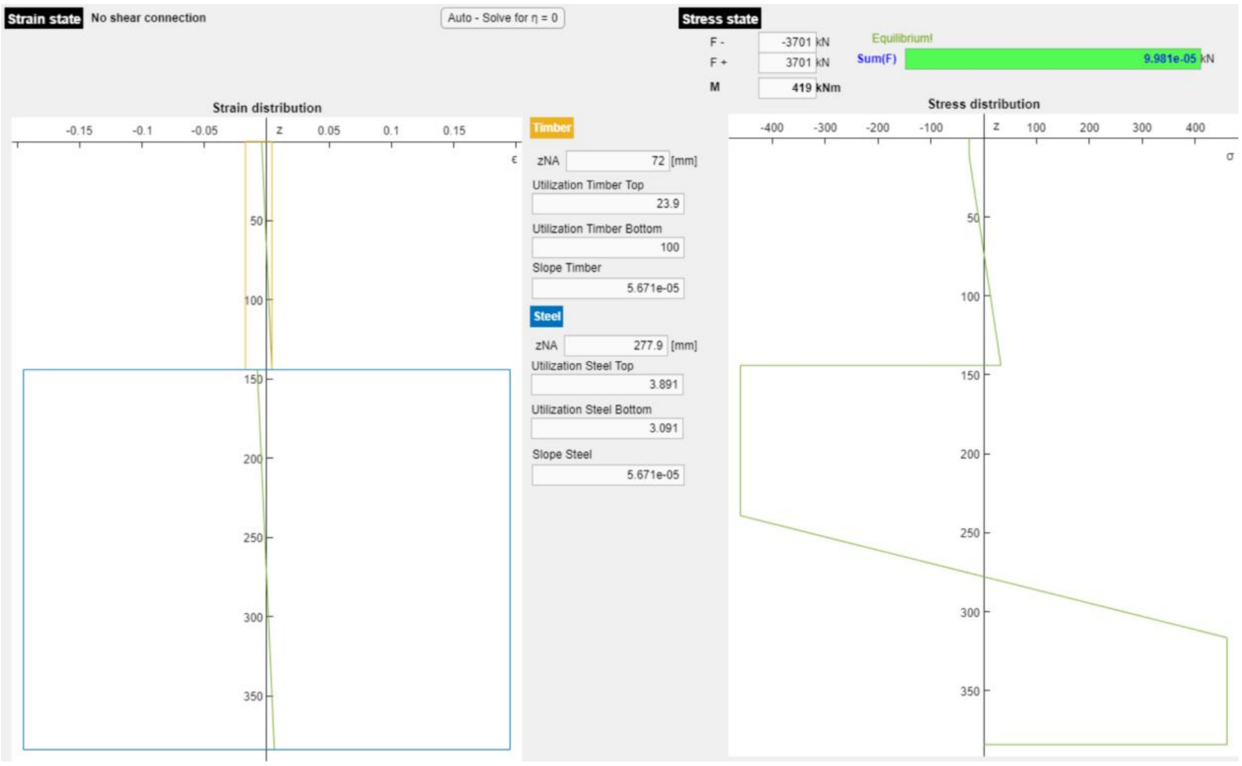


IPE 240, S460, t=2500x144

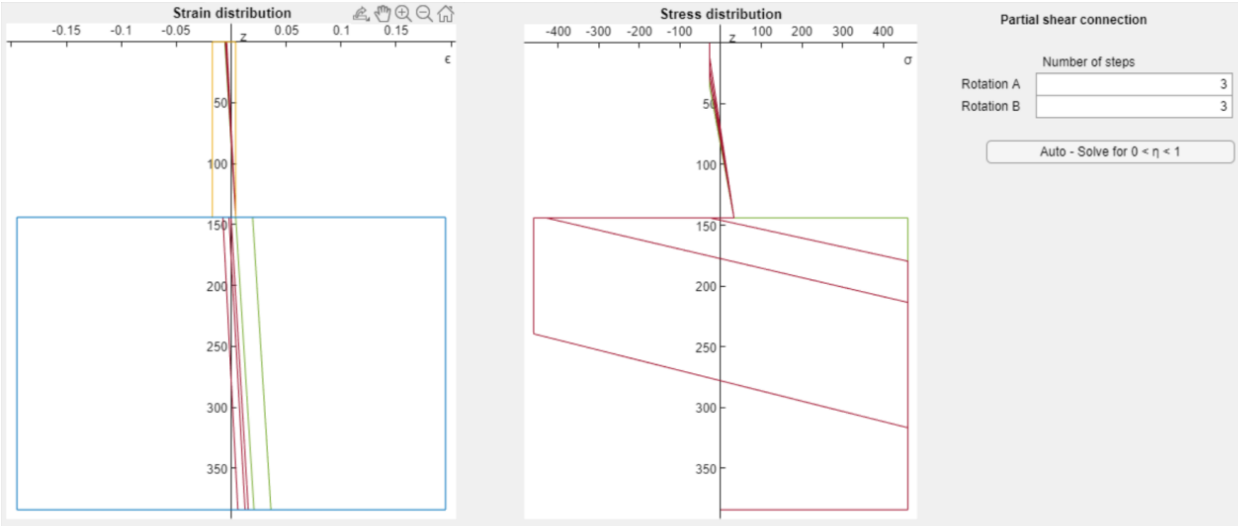
Results for full shear connection:



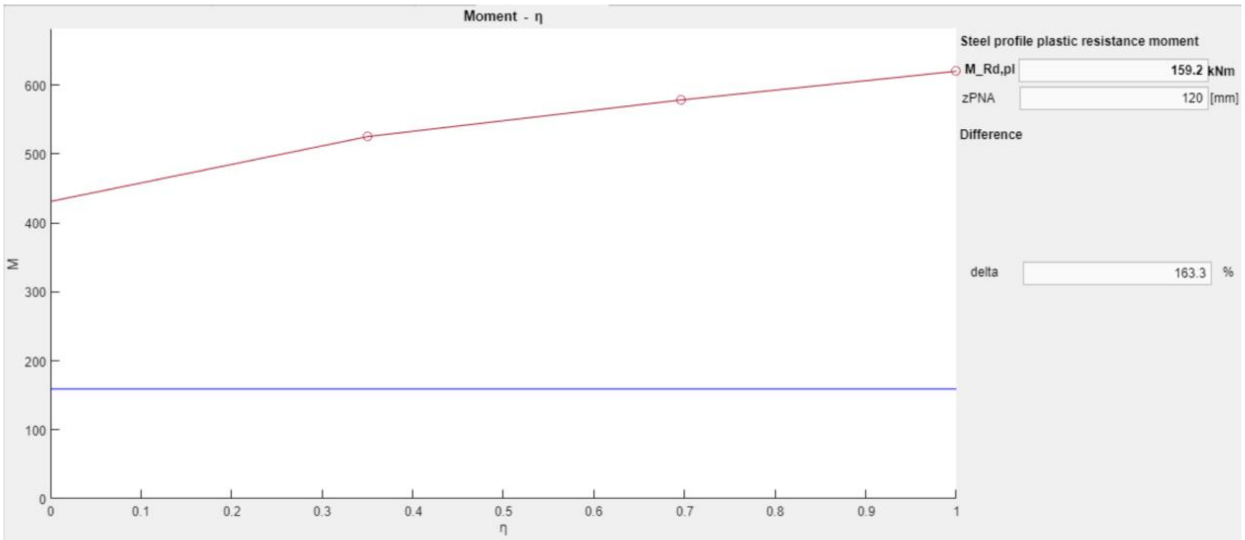
Results for no shear connection:



<u>Results for partial shear connection:</u>

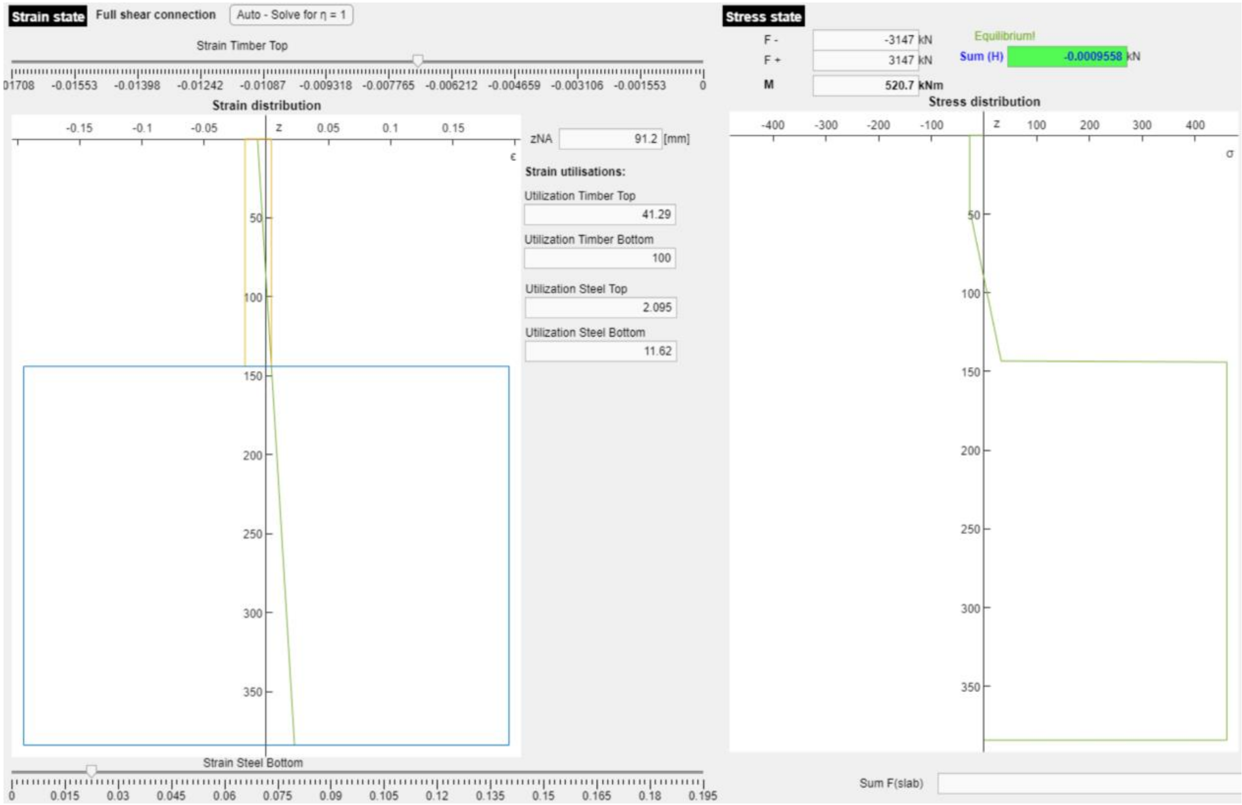


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0059	0.0041	0.0041	0.0207	-1.7105e+03	1.7105e+03	-9.9890e-04	1	620.0020
1	-0.0059	0.0041	0.0195	0.0361	-1.7105e+03	1.7105e+03	-9.9890e-04	1	620.0020
2	-0.0059	0.0041	0.0195	0.0361	-1.7105e+03	1.7105e+03	-9.9890e-04	1	620.0020
3	-0.0059	0.0041	0.0195	0.0361	-1.7105e+03	1.7105e+03	-9.9890e-04	1	620.0020
4	-0.0053	0.0041	-1.2379e-04	0.0155	-1.1905e+03	1.1895e+03	-0.9999	0.6960	578.2778
5	-0.0047	0.0041	-0.0020	0.0126	-599.4238	598.4264	-0.9974	0.3504	525.2555
6	-0.0041	0.0041	-0.0076	0.0060	78.4320	-79.4319	-0.9999	-0.0459	418.7631

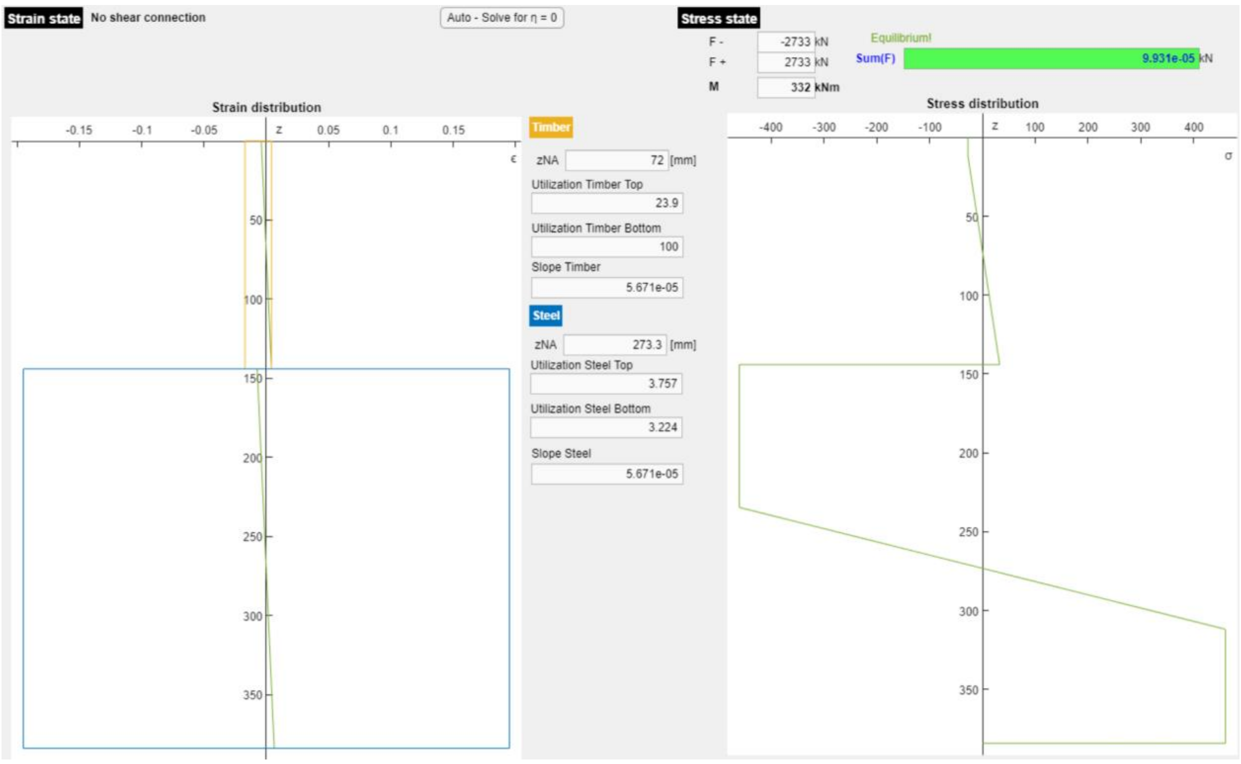


IPE 240, S460, t=1666x144

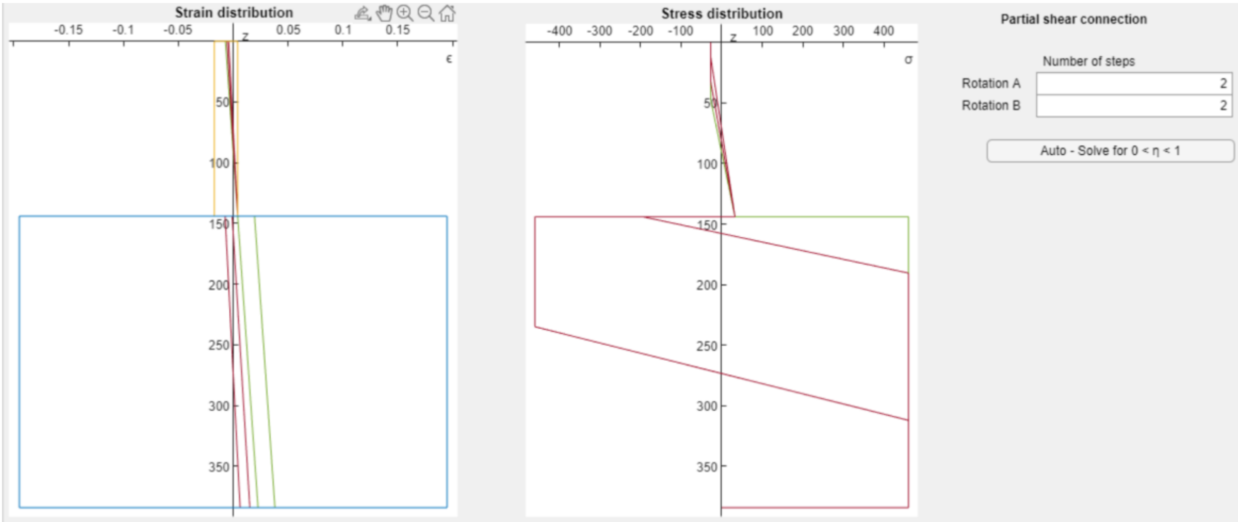
Results for full shear connection:



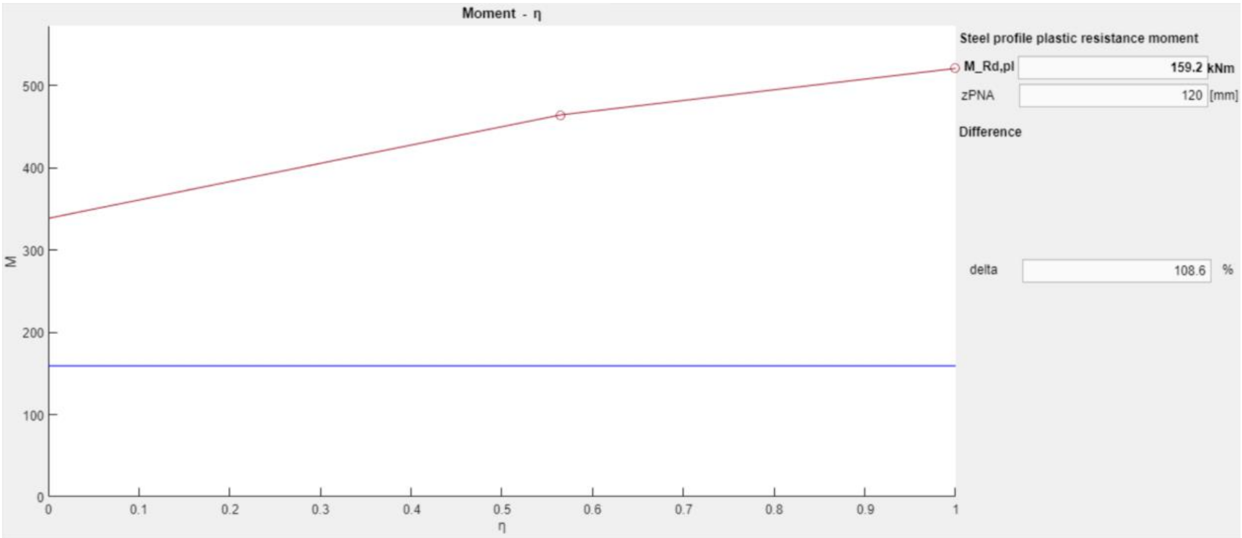
Results for no shear connection:



Results for partial shear connection:

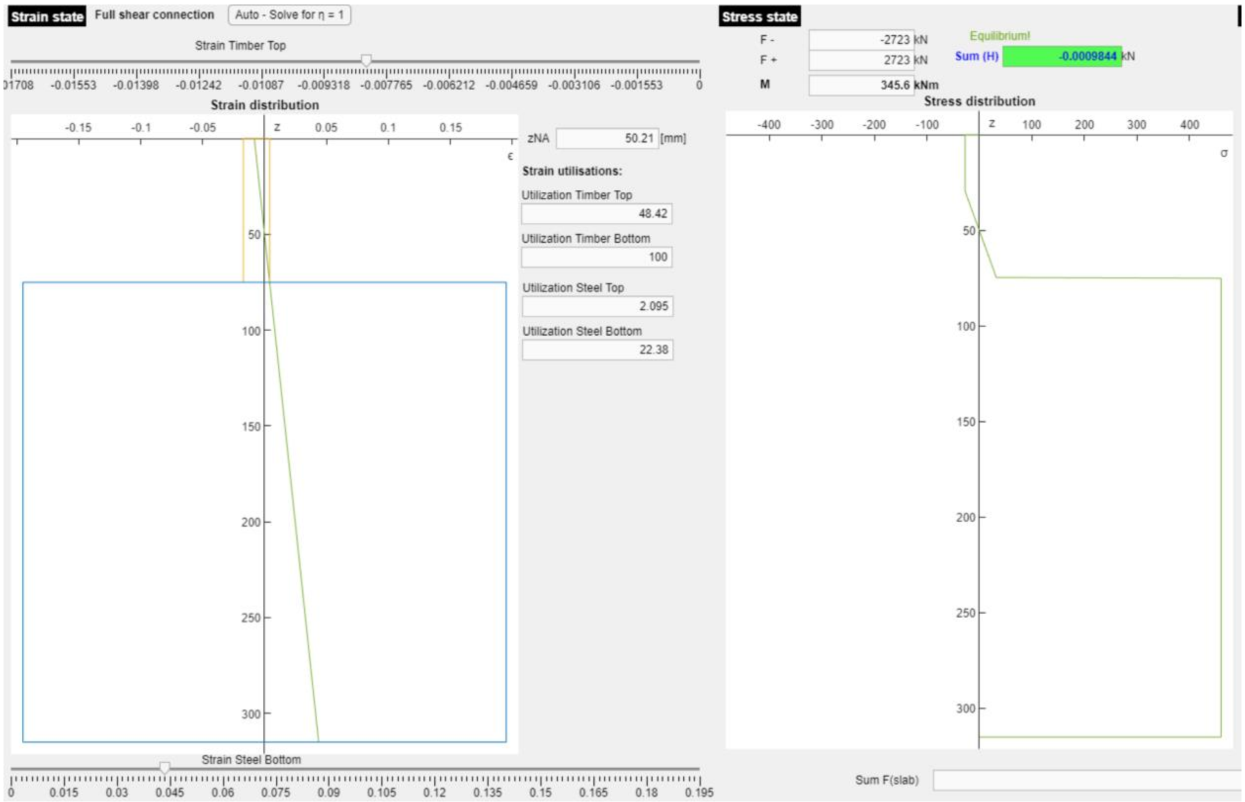


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0071	0.0041	0.0041	0.0226	-1.7105e+03	1.7105e+03	-9.5580e-04	1	520.7072
1	-0.0071	0.0041	0.0195	0.0381	-1.7105e+03	1.7105e+03	-9.5580e-04	1	520.7072
2	-0.0071	0.0041	0.0195	0.0381	-1.7105e+03	1.7105e+03	-9.5580e-04	1	520.7072
3	-0.0056	0.0041	-9.2421e-04	0.0152	-964.7300	963.7308	-0.9992	0.5640	464.1076
4	-0.0041	0.0041	-0.0073	0.0063	52.2671	-53.2656	-0.9985	-0.0306	331.7198

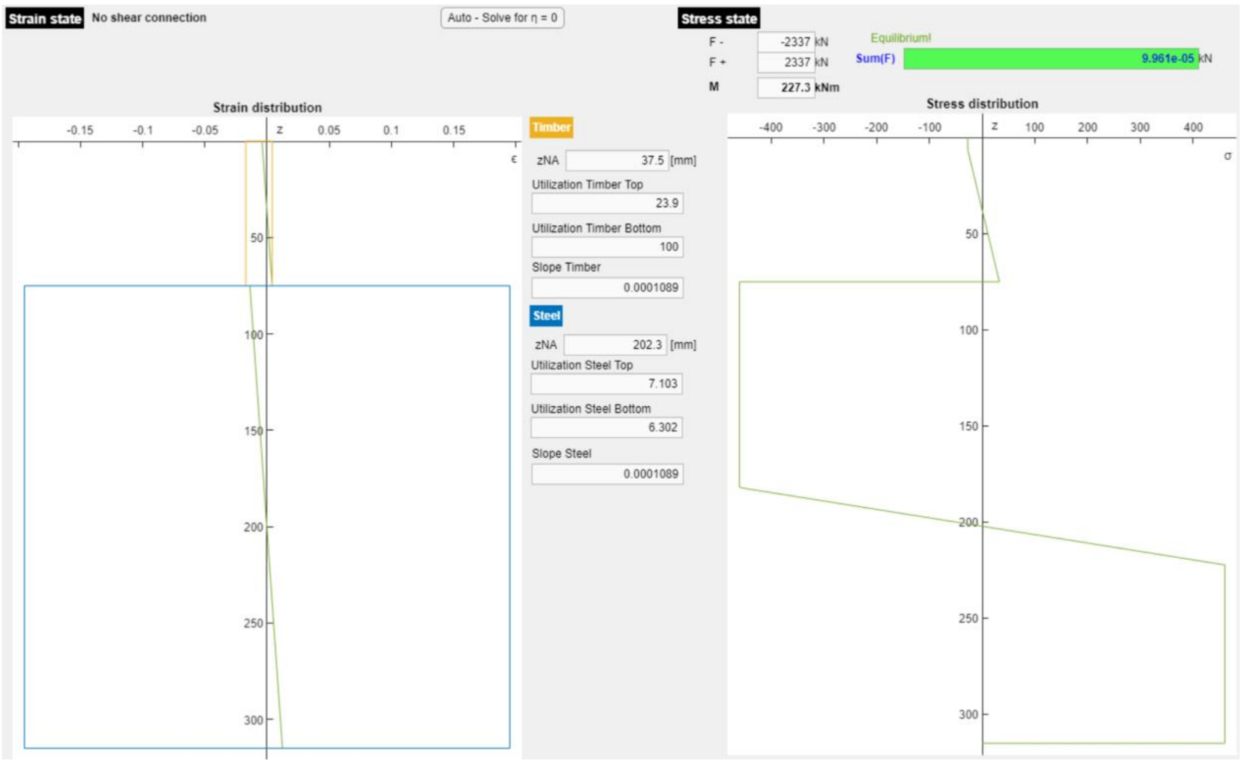


IPE 240, S460, t=2500x75

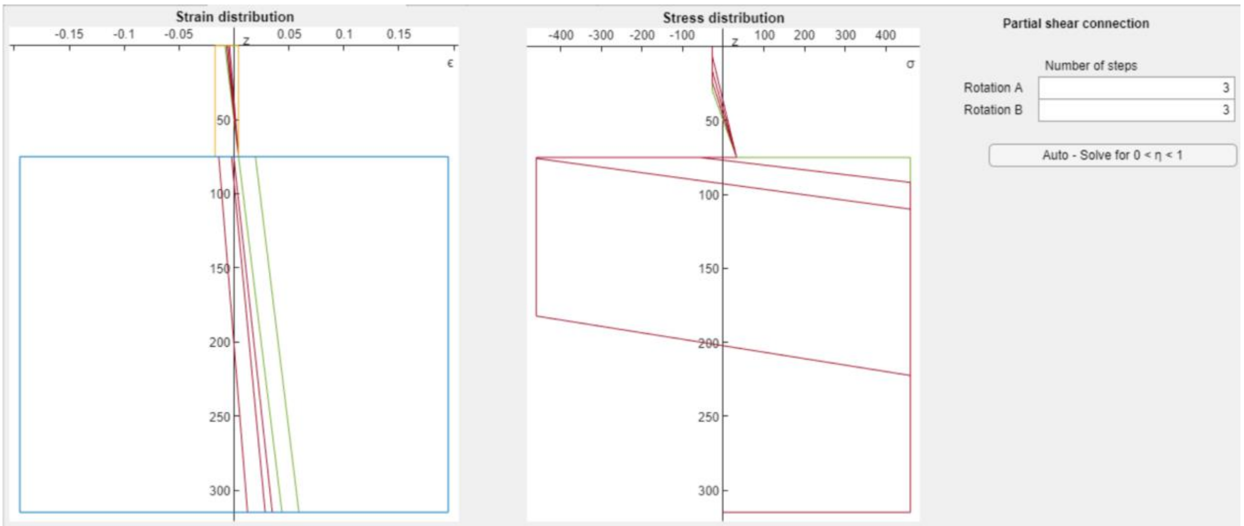
Results for full shear connection:



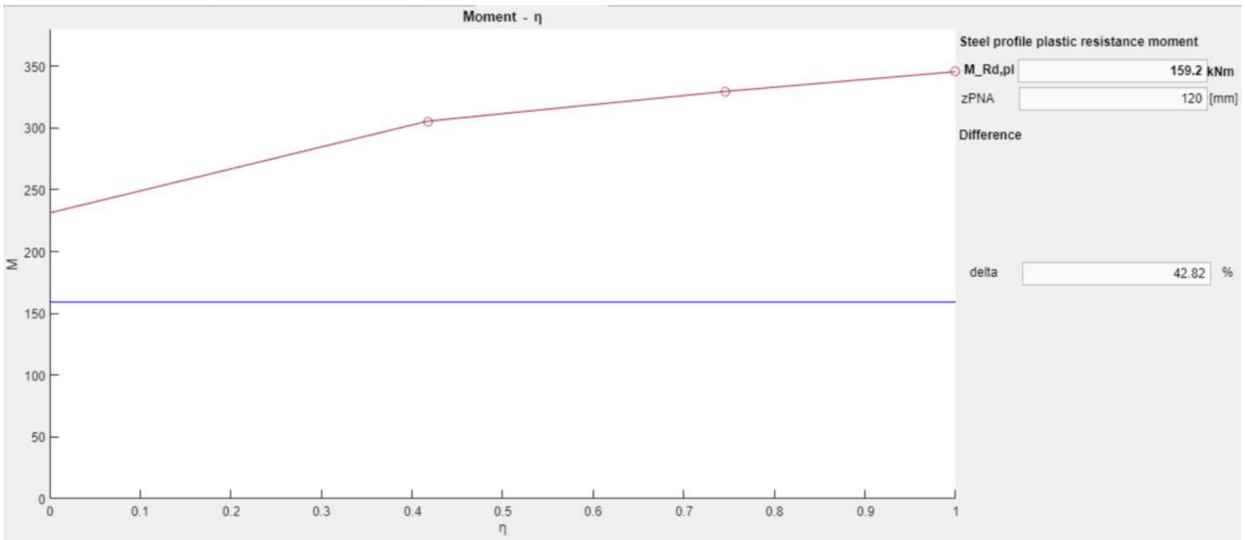
Results for no shear connection:



Results for partial shear connection:

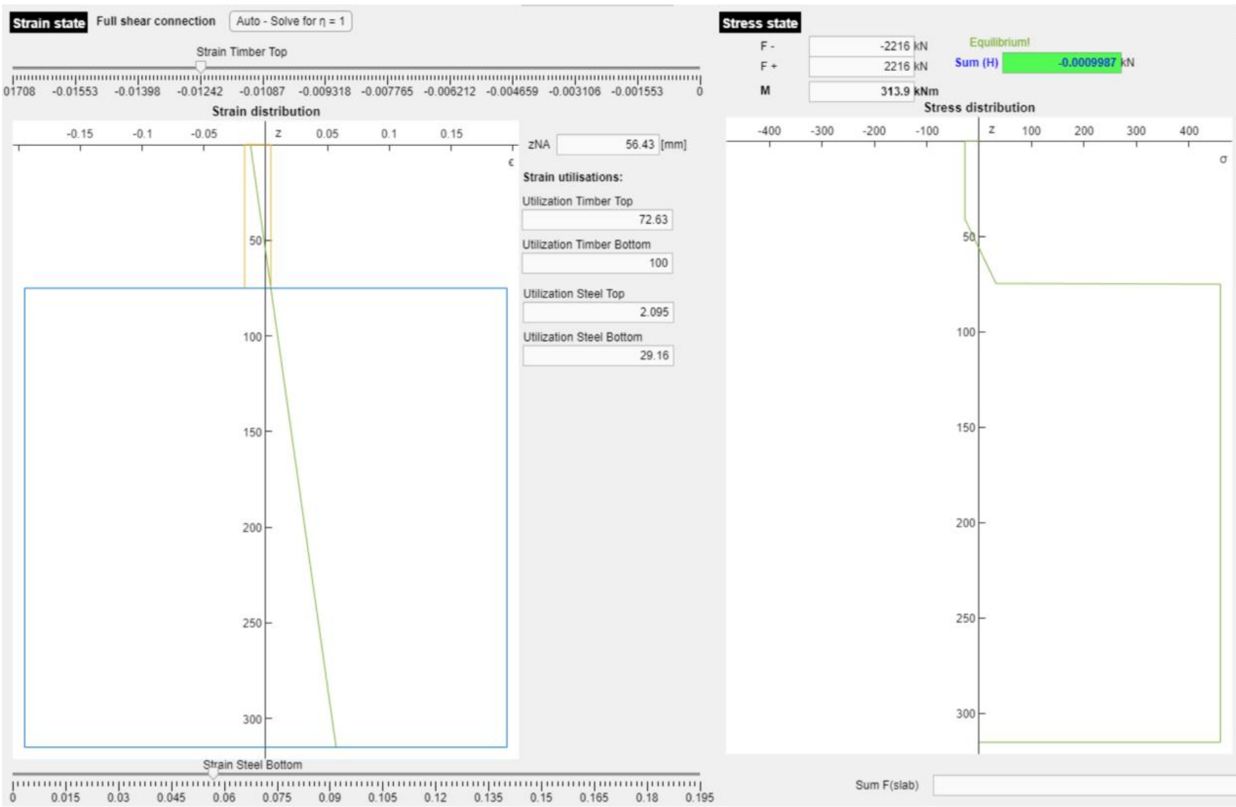


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0083	0.0041	0.0041	0.0436	-1.7105e+03	1.7105e+03	-9.8438e-04	1	345.6279
1	-0.0083	0.0041	0.0195	0.0590	-1.7105e+03	1.7105e+03	-9.8438e-04	1	345.6279
2	-0.0083	0.0041	0.0195	0.0590	-1.7105e+03	1.7105e+03	-9.8438e-04	1	345.6279
3	-0.0083	0.0041	0.0195	0.0590	-1.7105e+03	1.7105e+03	-9.8438e-04	1	345.6279
4	-0.0069	0.0041	-2.7184e-04	0.0348	-1.2755e+03	1.2745e+03	-0.9995	0.7457	329.6277
5	-0.0055	0.0041	-0.0023	0.0283	-713.4341	712.4417	-0.9924	0.4171	305.5351
6	-0.0041	0.0041	-0.0139	0.0123	40.8500	-41.8480	-0.9980	-0.0239	227.1092

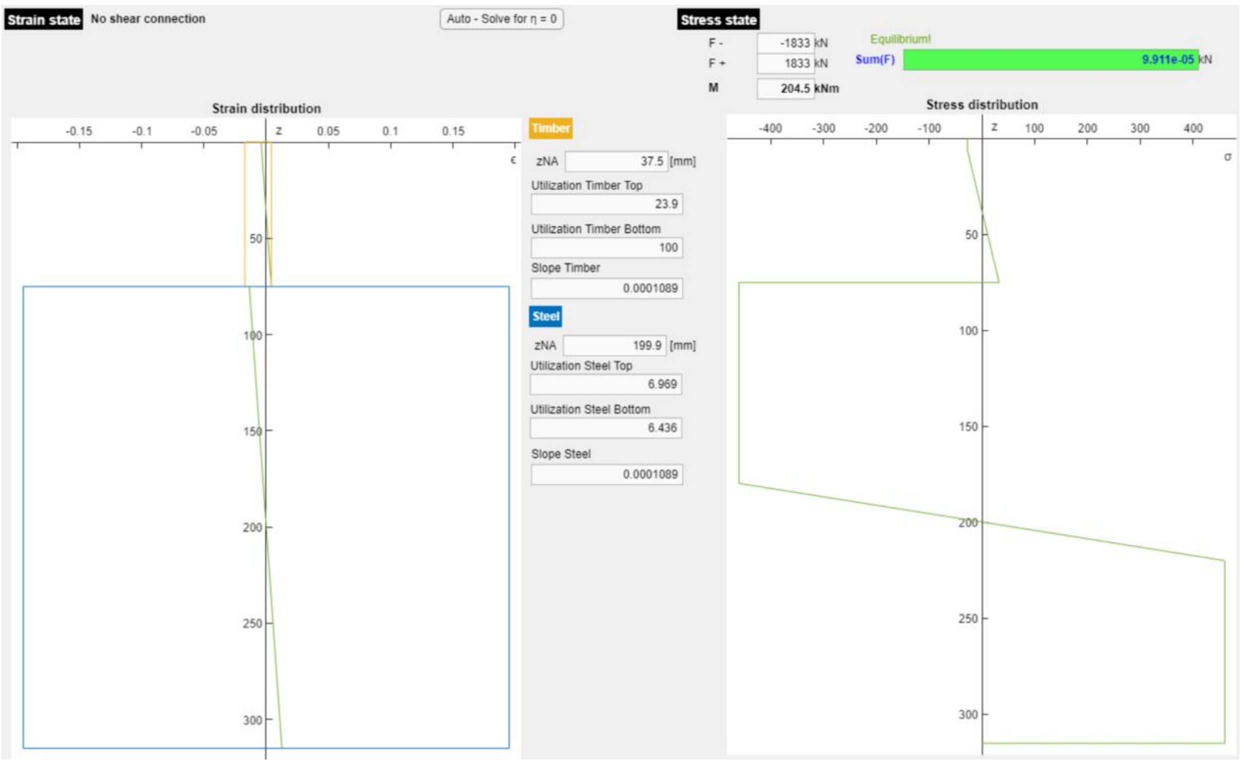


IPE 240, S460, t=1666x75

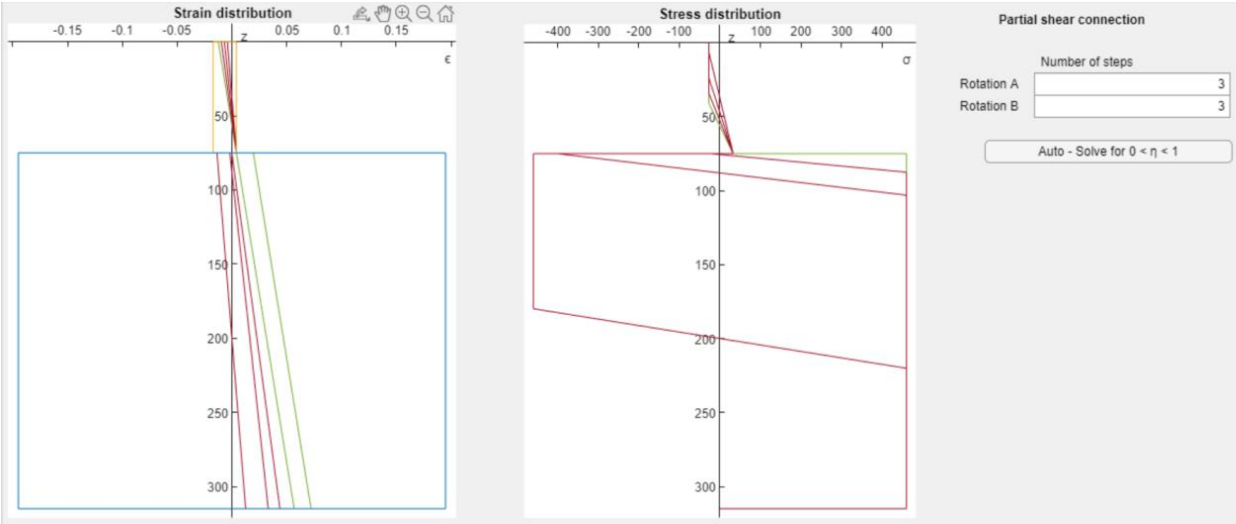
Results for full shear connection:



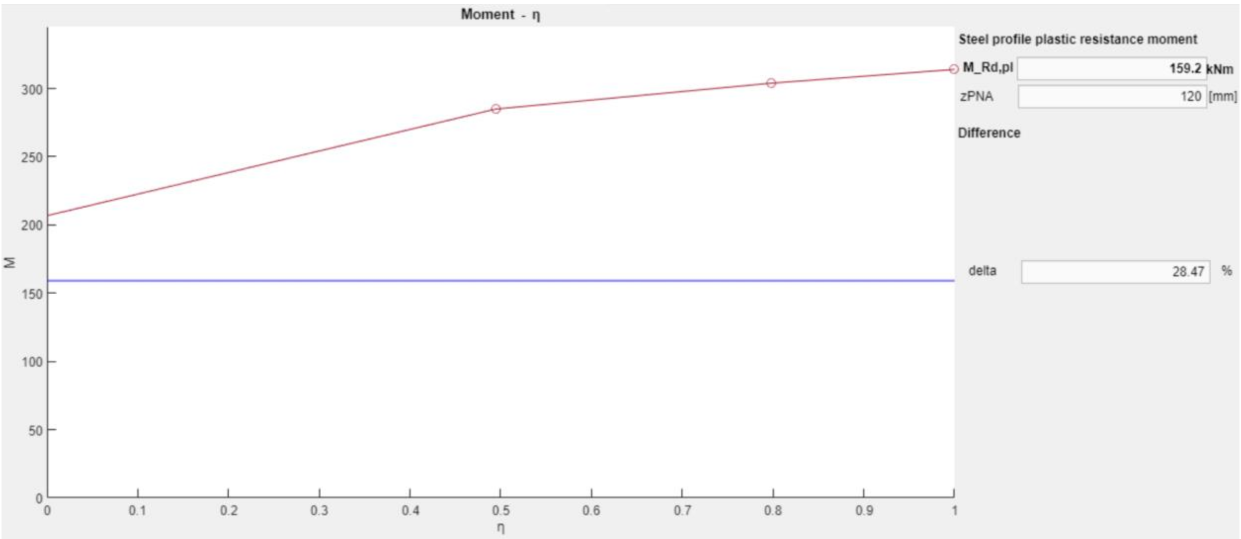
Results for no shear connection:



Results for partial shear connection:

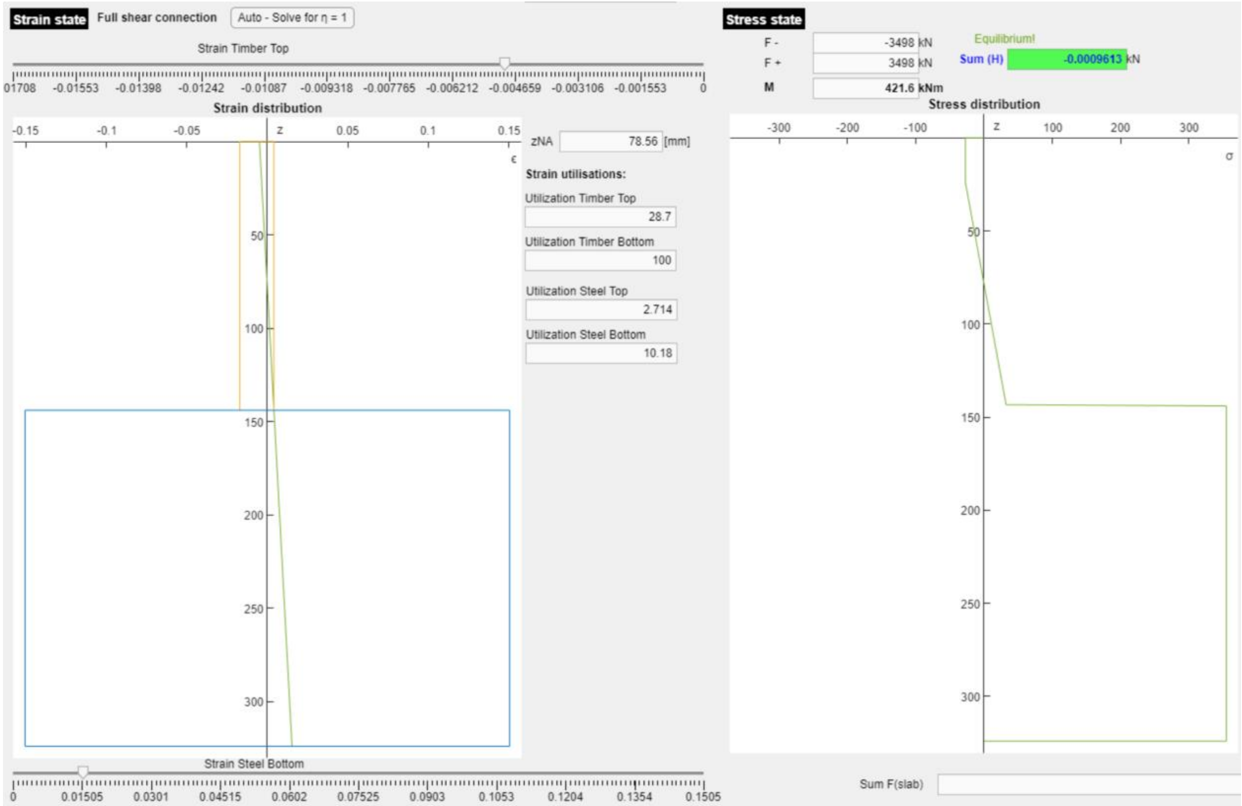


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0124	0.0041	0.0041	0.0569	-1.7105e+03	1.7105e+03	-9.9868e-04	1	313.9491
1	-0.0124	0.0041	0.0195	0.0723	-1.7105e+03	1.7105e+03	-9.9868e-04	1	313.9491
2	-0.0124	0.0041	0.0195	0.0723	-1.7105e+03	1.7105e+03	-9.9868e-04	1	313.9491
3	-0.0124	0.0041	0.0195	0.0723	-1.7105e+03	1.7105e+03	-9.9868e-04	1	313.9491
4	-0.0096	0.0041	-1.0268e-04	0.0438	-1.3656e+03	1.3646e+03	-0.9997	0.7984	303.8982
5	-0.0069	0.0041	-0.0019	0.0331	-845.8177	844.8297	-0.9880	0.4945	284.9247
6	-0.0041	0.0041	-0.0136	0.0125	27.2224	-28.2189	-0.9965	-0.0159	204.2820

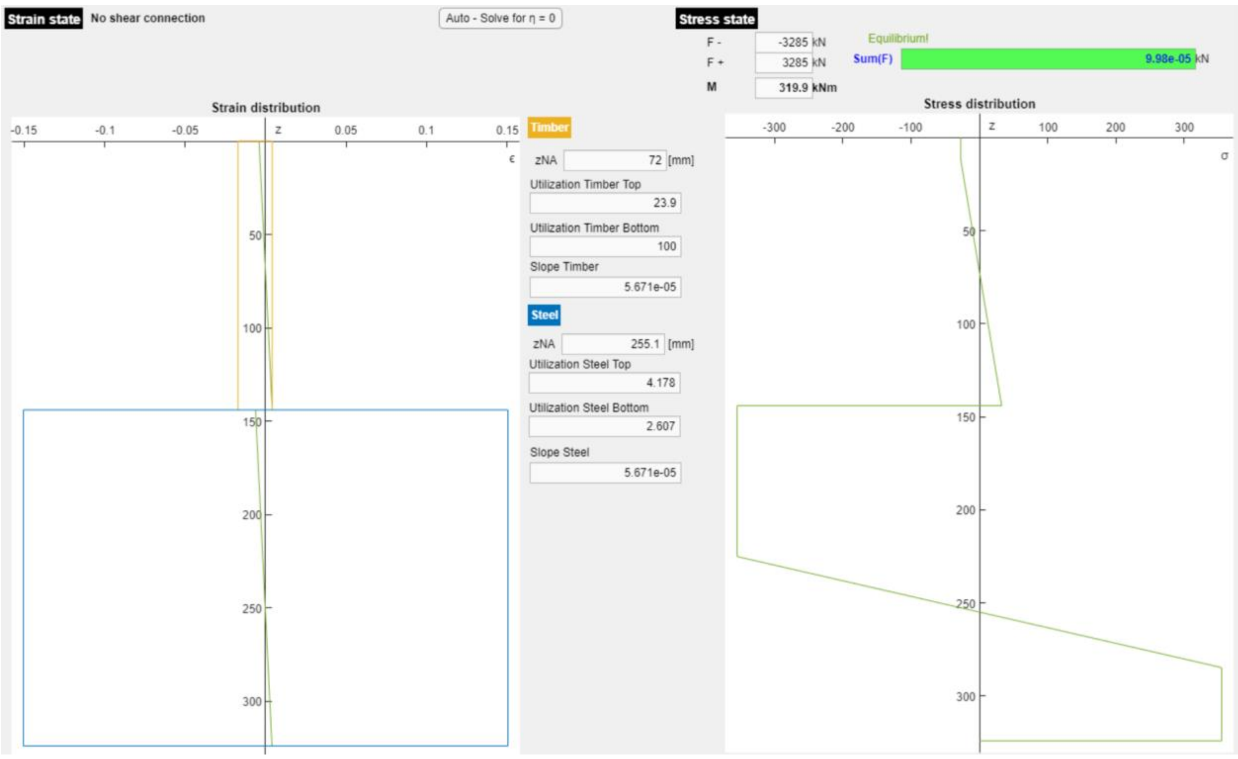


IPE 180, S355, t=2500x144

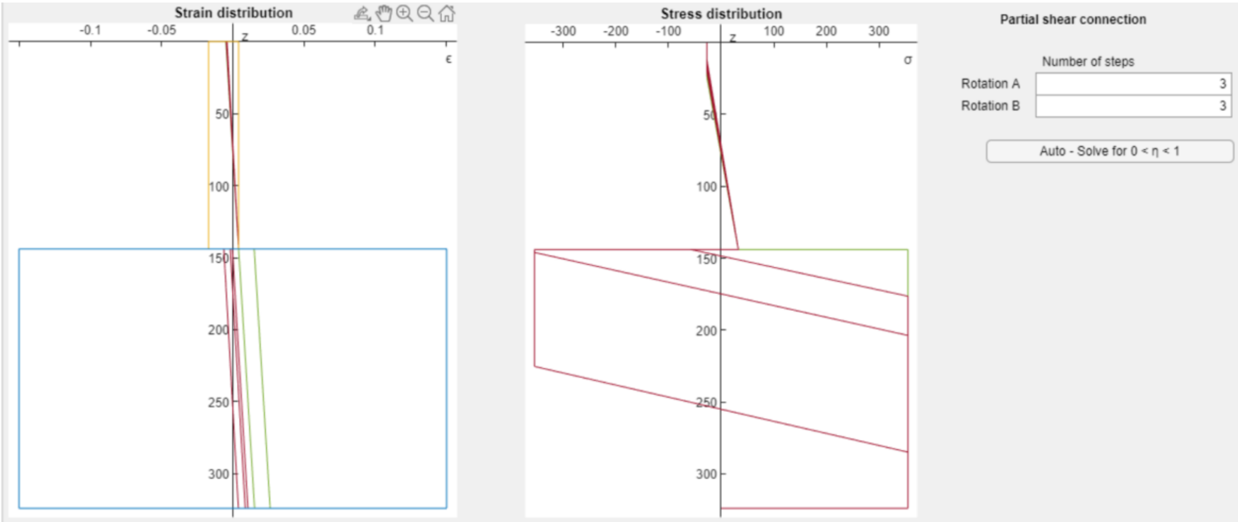
Results for full shear connection:



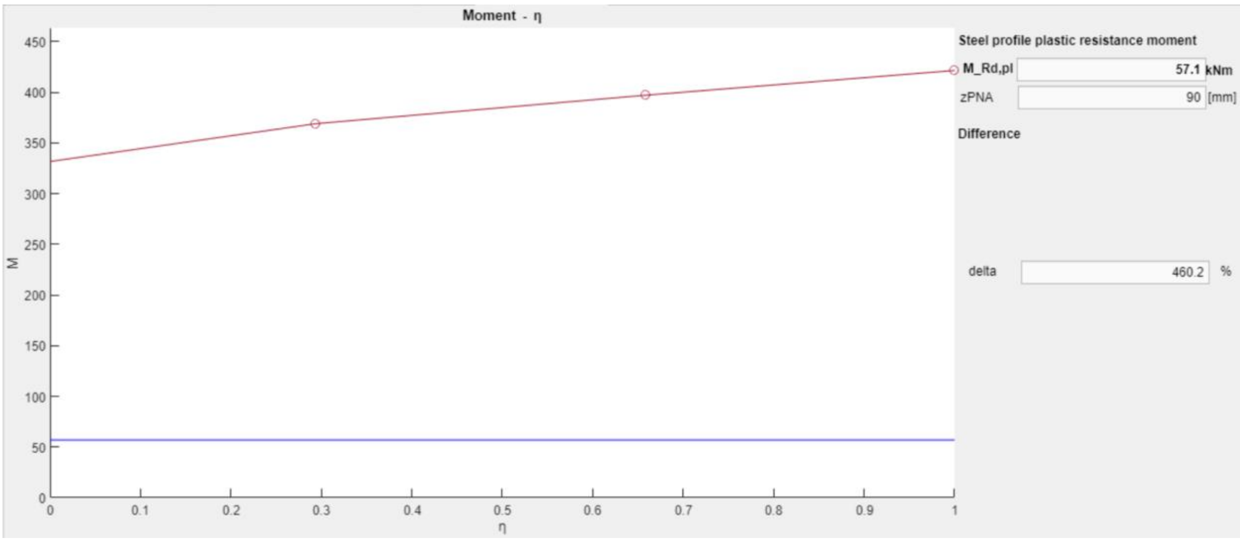
Results for no shear connection:



Results for partial shear connection:

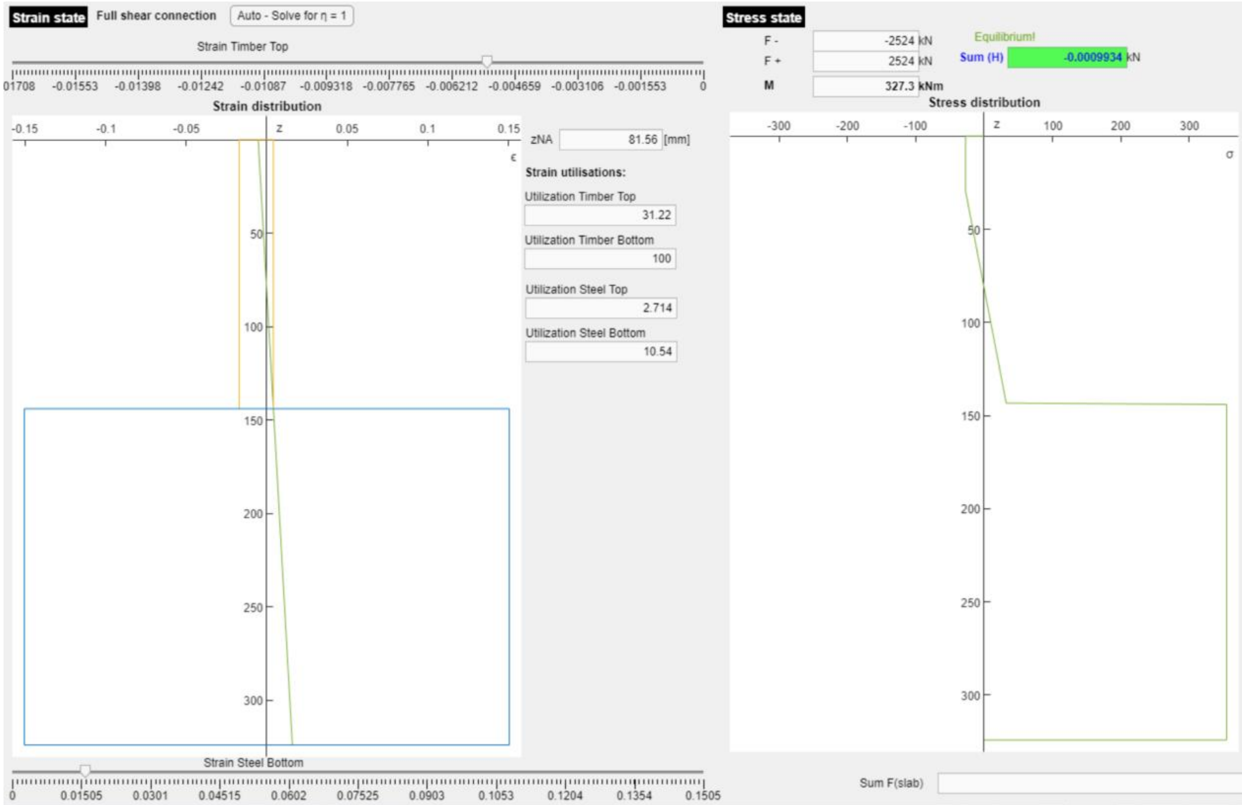


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0049	0.0041	0.0041	0.0153	-825.4470	825.4460	-0.0010	1.0000	421.5970
1.0000	-0.0049	0.0041	0.0150	0.0263	-825.4470	825.4460	-0.0010	1.0000	421.5970
2.0000	-0.0049	0.0041	0.0150	0.0263	-825.4470	825.4460	-0.0010	1.0000	421.5970
3.0000	-0.0049	0.0041	0.0150	0.0263	-825.4470	825.4460	-0.0010	1.0000	421.5970
4.0000	-0.0046	0.0041	-0.0003	0.0106	-543.0216	542.0219	-0.9997	0.6579	397.1378
5.0000	-0.0044	0.0041	-0.0018	0.0087	-242.3381	241.3388	-0.9993	0.2936	369.0675
6.0000	-0.0041	0.0041	-0.0063	0.0039	78.4320	-79.4304	-0.9984	-0.0950	319.6614

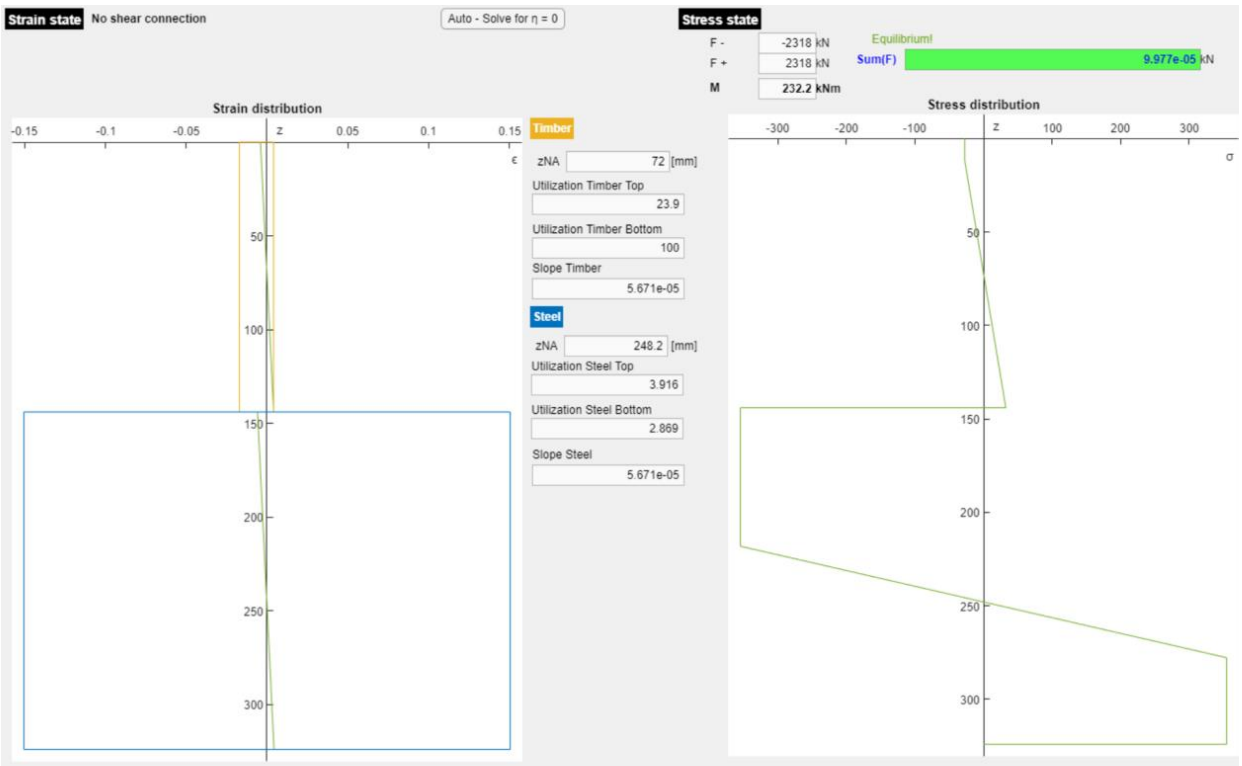


IPE 180, S355, t=1666x144

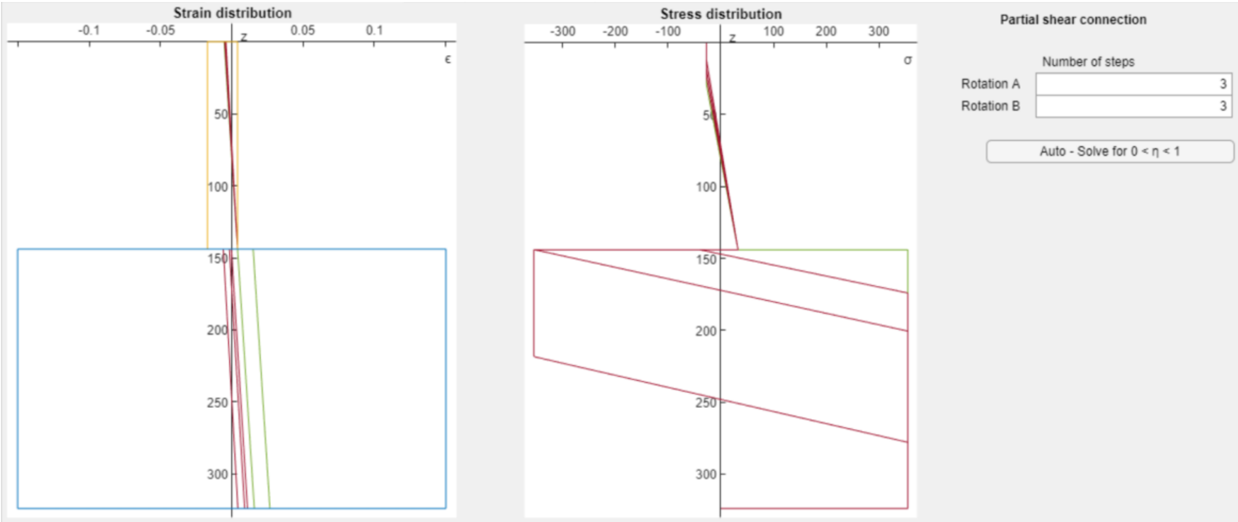
Results for full shear connection:



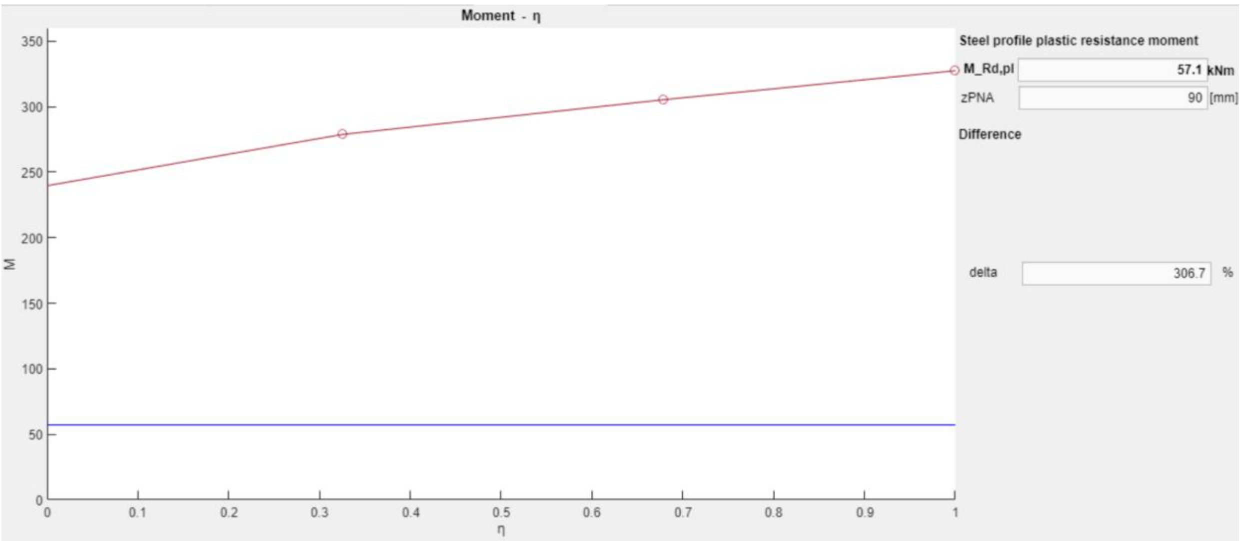
Results for no shear connection:



Results for partial shear connection:

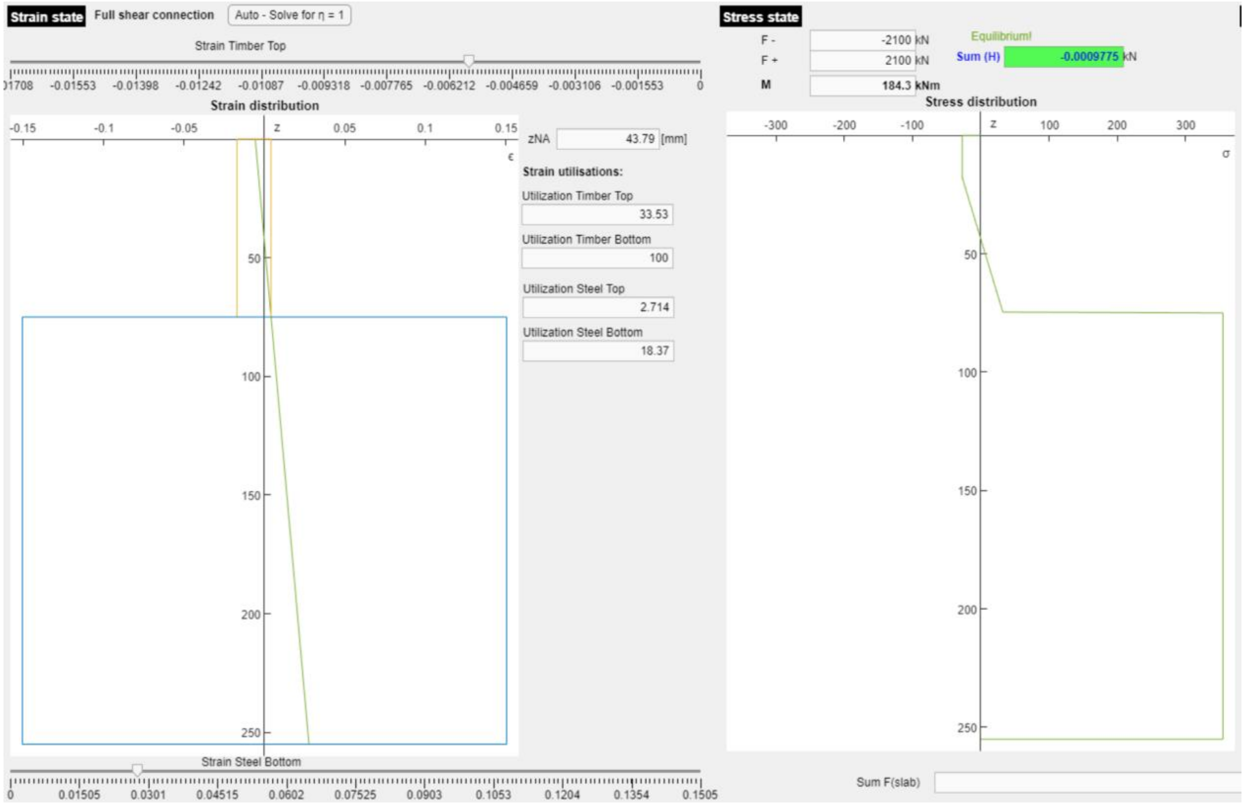


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0053	0.0041	0.0041	0.0159	-825.4470	825.4460	-0.0010	1.0000	327.2936
1.0000	-0.0053	0.0041	0.0150	0.0268	-825.4470	825.4460	-0.0010	1.0000	327.2936
2.0000	-0.0053	0.0041	0.0150	0.0268	-825.4470	825.4460	-0.0010	1.0000	327.2936
3.0000	-0.0053	0.0041	0.0150	0.0268	-825.4470	825.4460	-0.0010	1.0000	327.2936
4.0000	-0.0049	0.0041	-0.0002	0.0111	-559.9730	558.9736	-0.9993	0.6784	305.1742
5.0000	-0.0045	0.0041	-0.0017	0.0090	-268.7270	267.7317	-0.9953	0.3256	278.7535
6.0000	-0.0041	0.0041	-0.0059	0.0043	52.2671	-53.2610	-0.9939	-0.0633	231.9908

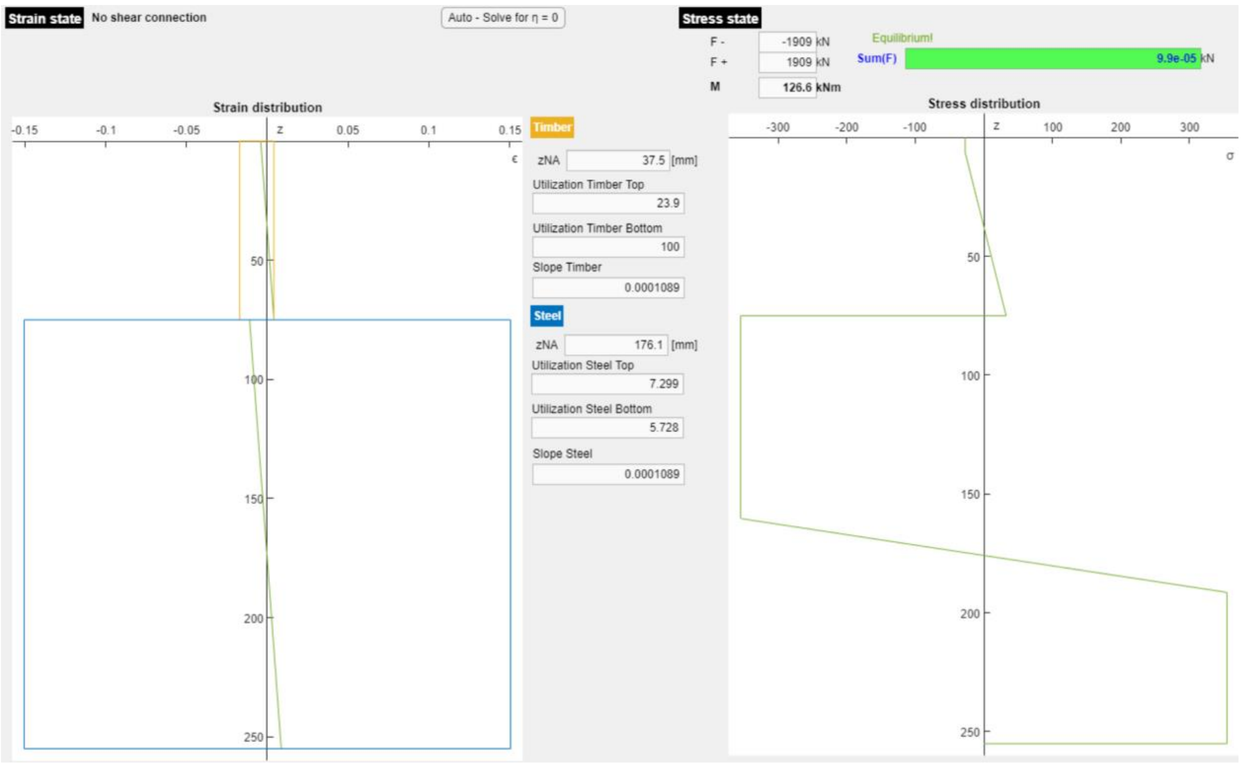


IPE 180, S355, t=2500x75

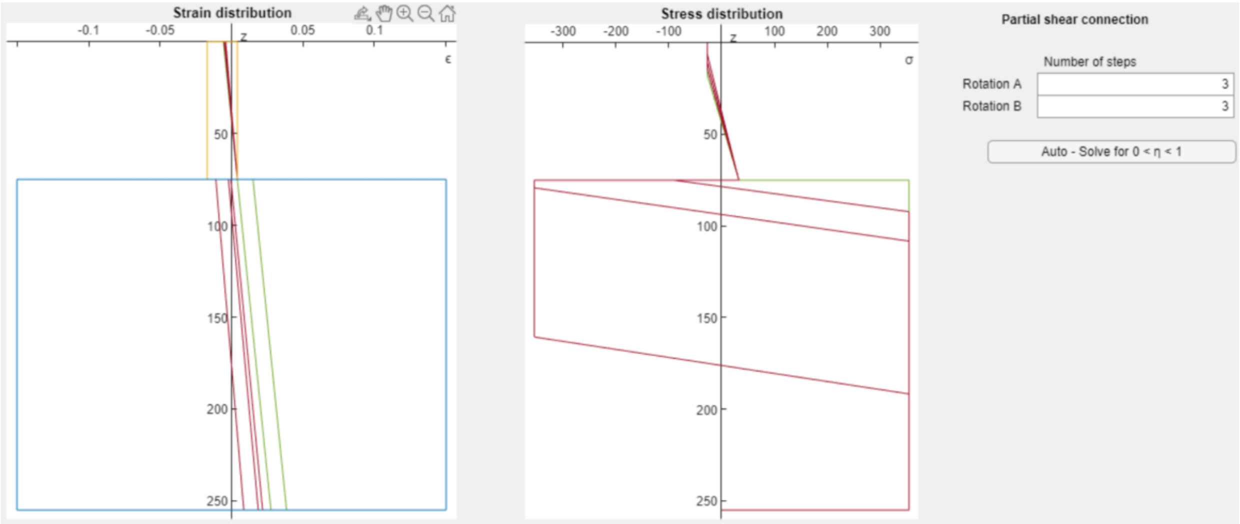
Results for full shear connection:



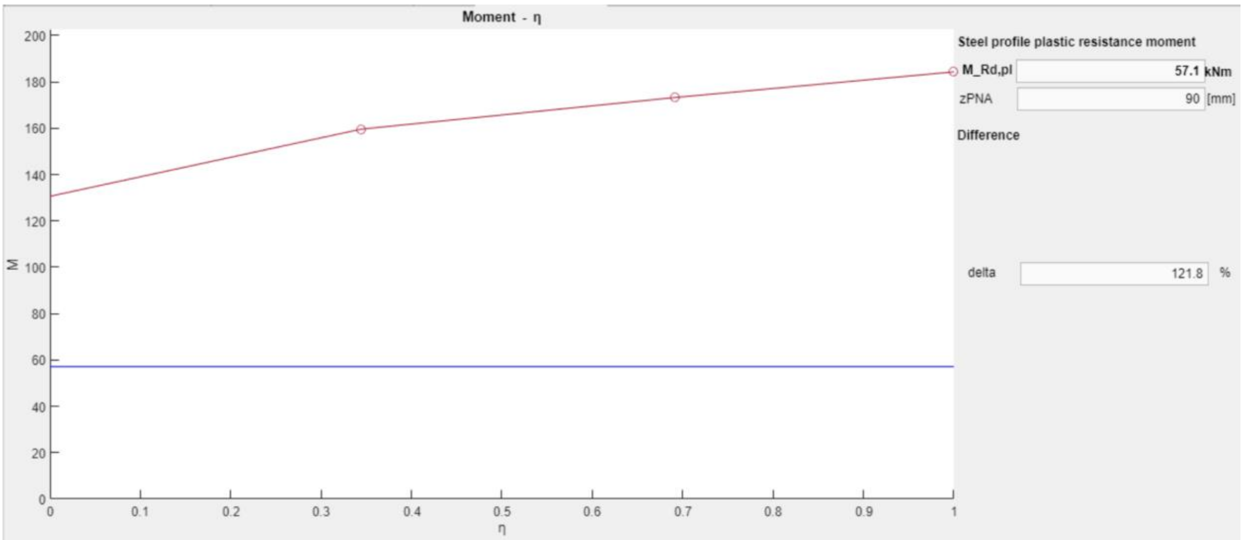
Results for no shear connection:



Results for partial shear connection:

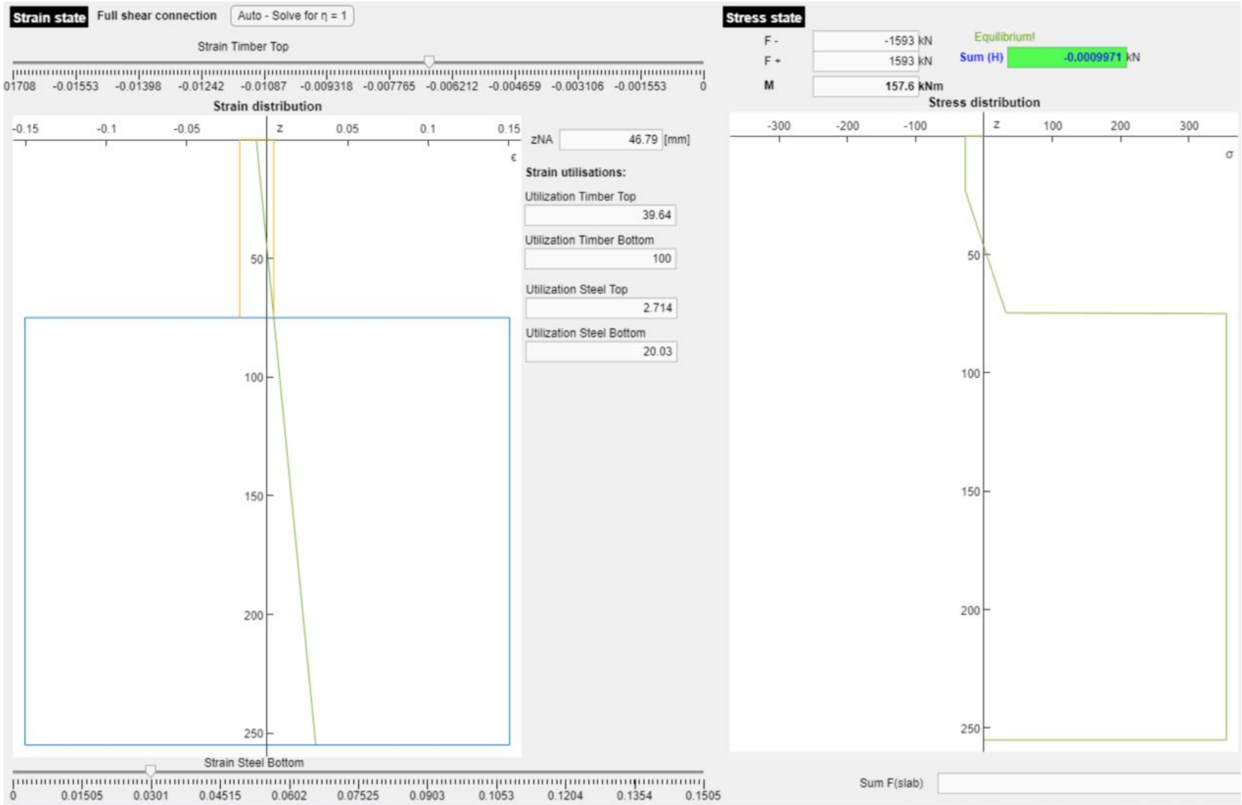


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0057	0.0041	0.0041	0.0276	-825.4470	825.4460	-0.0010	1.0000	184.3146
1.0000	-0.0057	0.0041	0.0150	0.0386	-825.4470	825.4460	-0.0010	1.0000	184.3146
2.0000	-0.0057	0.0041	0.0150	0.0386	-825.4470	825.4460	-0.0010	1.0000	184.3146
3.0000	-0.0057	0.0041	0.0150	0.0386	-825.4470	825.4460	-0.0010	1.0000	184.3146
4.0000	-0.0052	0.0041	-0.0004	0.0218	-570.8880	569.8882	-0.9997	0.6916	173.2600
5.0000	-0.0046	0.0041	-0.0022	0.0187	-284.2744	283.2795	-0.9950	0.3444	159.6168
6.0000	-0.0041	0.0041	-0.0110	0.0086	40.8500	-41.8432	-0.9932	-0.0495	126.4590

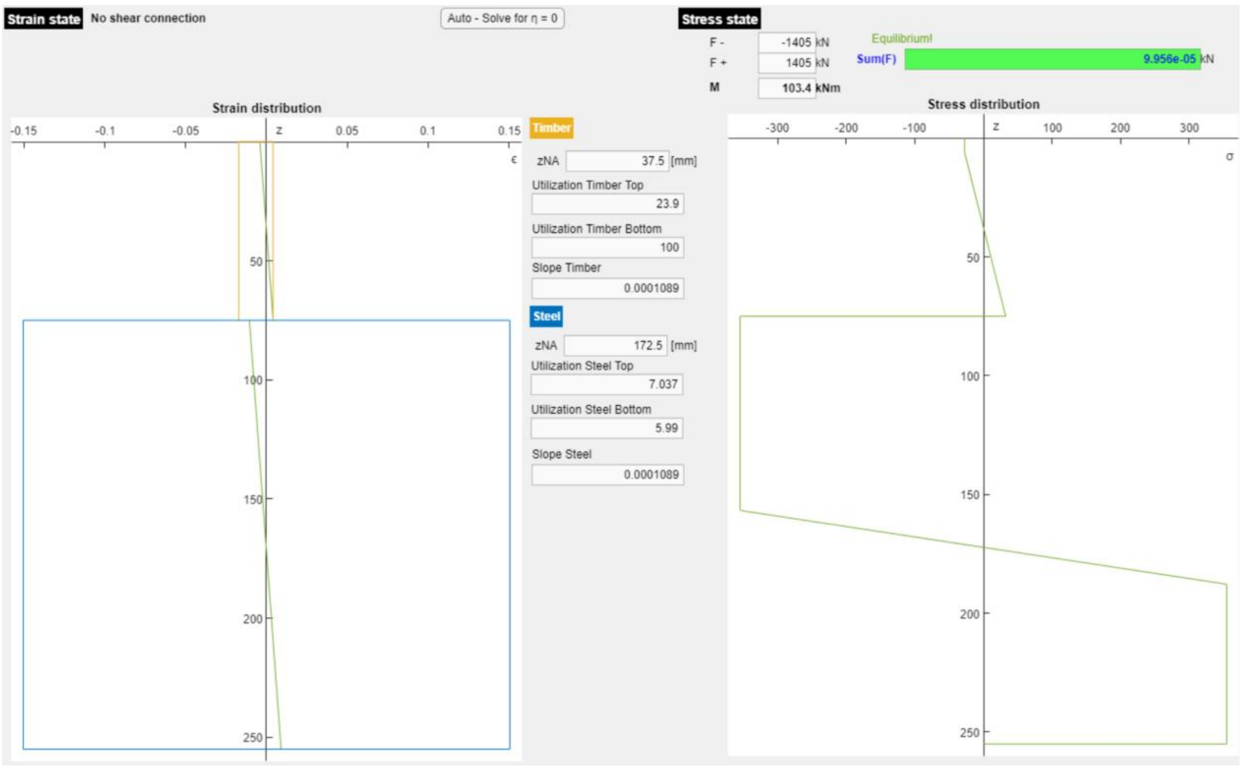


IPE 180, S355, t=1666x75

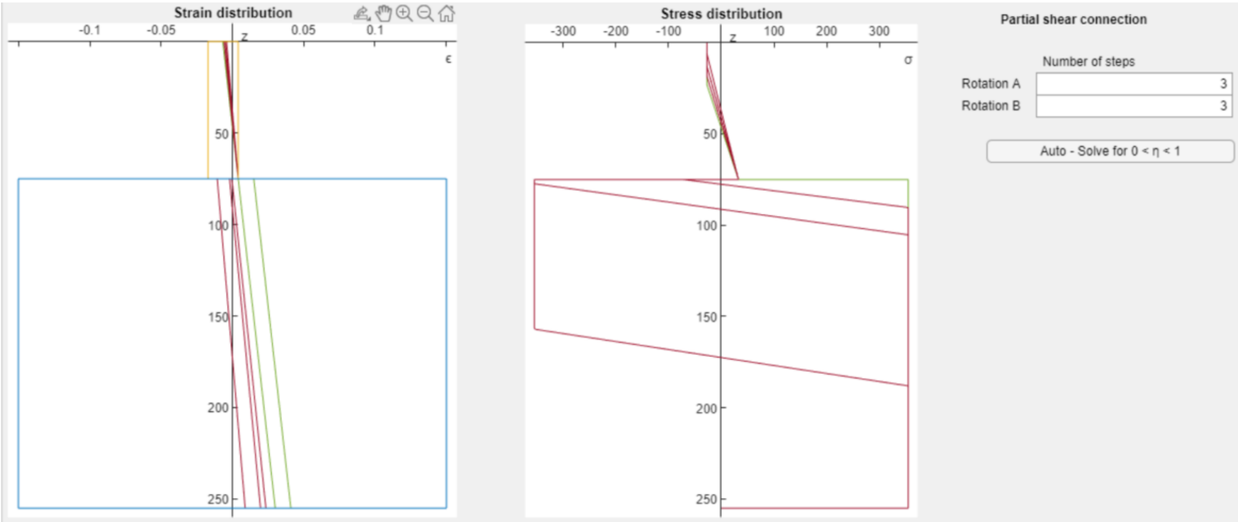
Results for full shear connection:



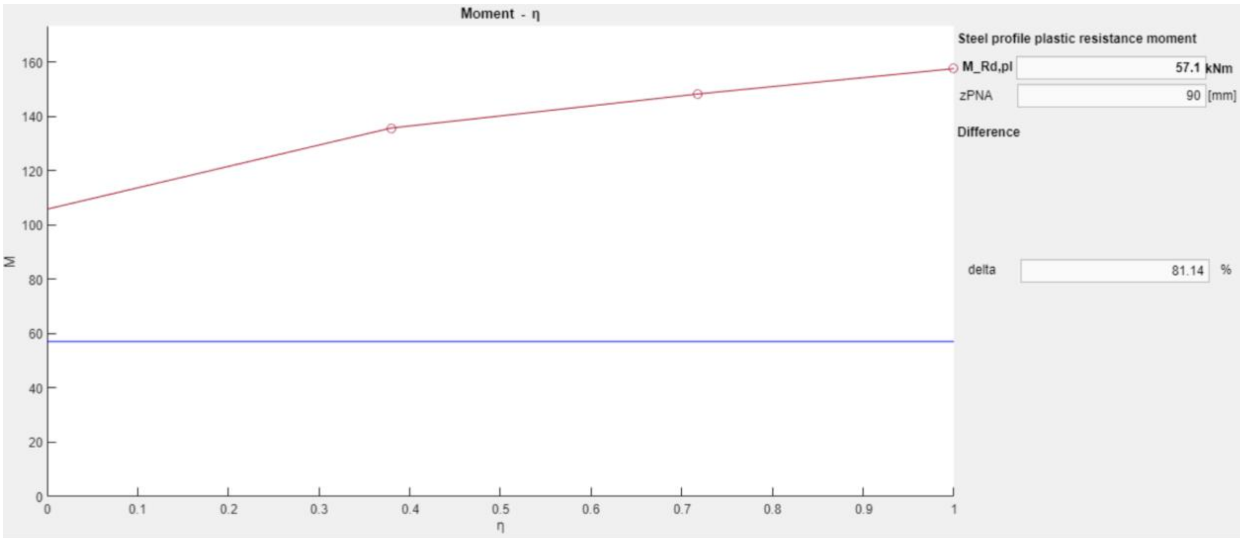
Results for no shear connection:



Results for partial shear connection:

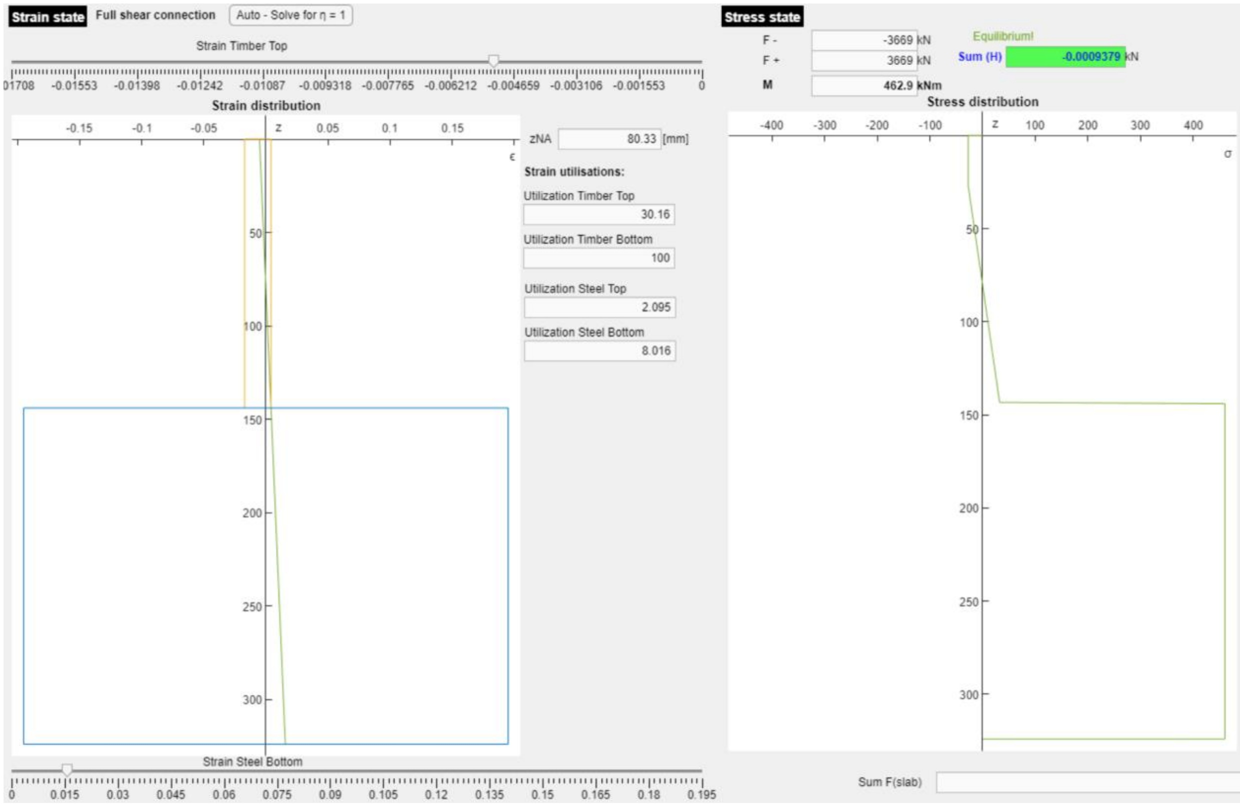


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0068	0.0041	0.0041	0.0301	-825.4470	825.4460	-0.0010	1.0000	157.6287
1.0000	-0.0068	0.0041	0.0150	0.0411	-825.4470	825.4460	-0.0010	1.0000	157.6287
2.0000	-0.0068	0.0041	0.0150	0.0411	-825.4470	825.4460	-0.0010	1.0000	157.6287
3.0000	-0.0068	0.0041	0.0150	0.0411	-825.4470	825.4460	-0.0010	1.0000	157.6287
4.0000	-0.0059	0.0041	-0.0003	0.0236	-592.3711	591.3716	-0.9995	0.7176	148.2859
5.0000	-0.0050	0.0041	-0.0020	0.0198	-313.2089	312.2126	-0.9963	0.3794	135.7510
6.0000	-0.0041	0.0041	-0.0106	0.0090	27.2224	-28.2133	-0.9909	-0.0330	103.2663

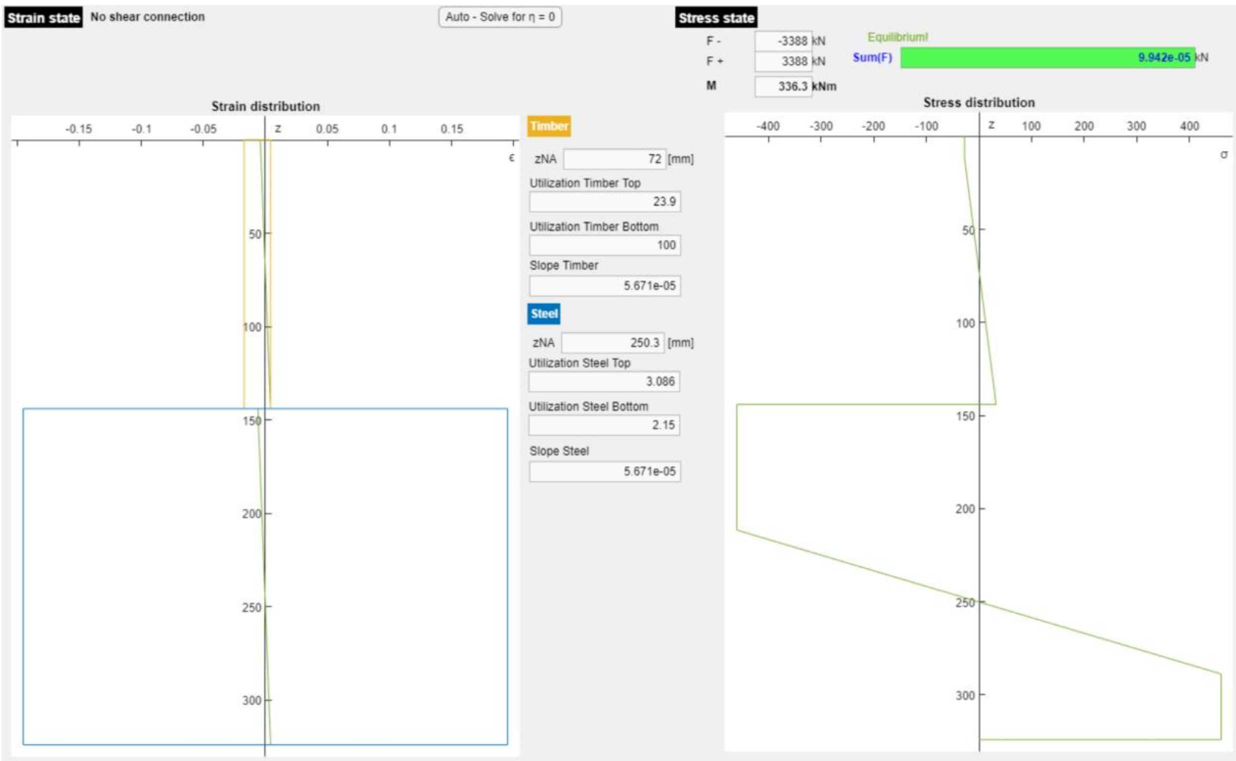


IPE 180, S460, t=2500x144

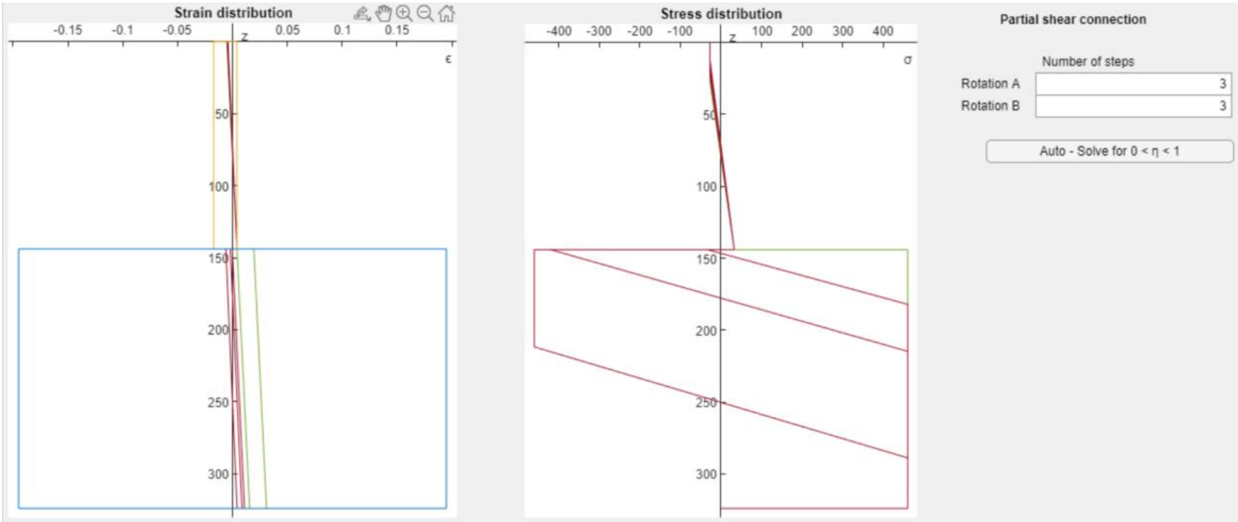
Results for full shear connection:



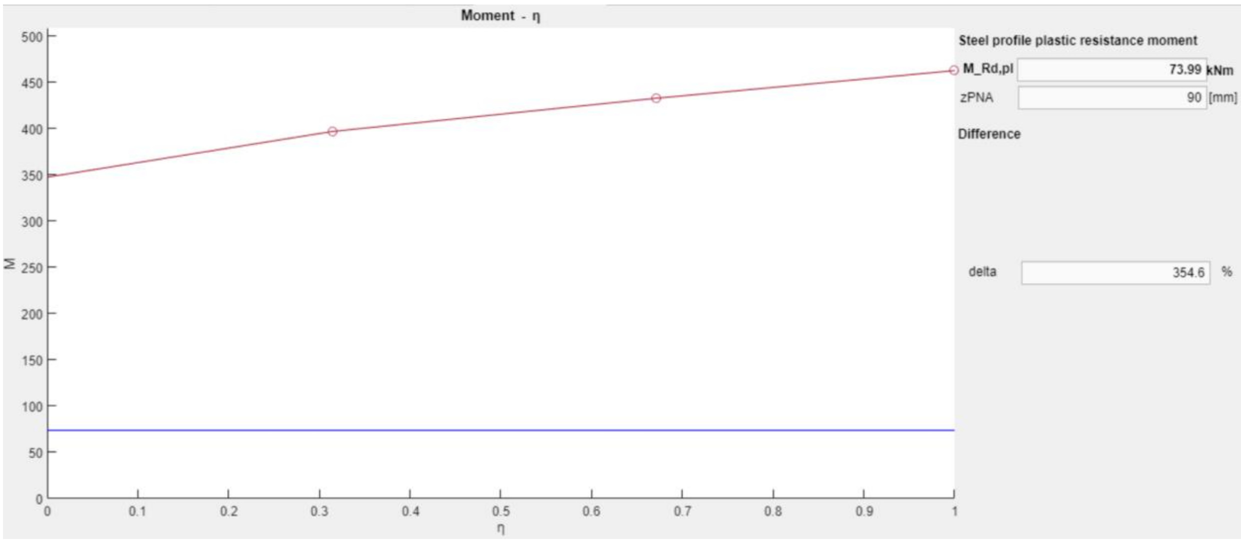
Results for no shear connection:



Results for partial shear connection:

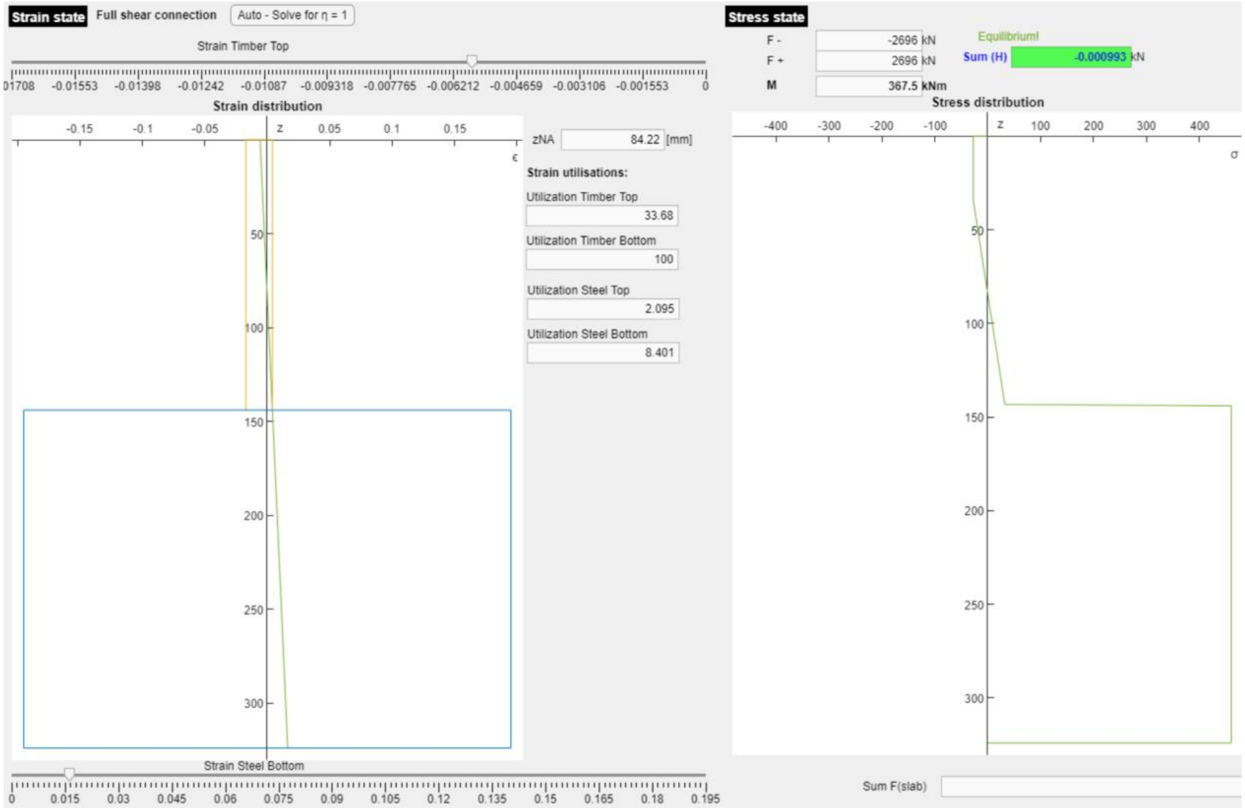


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0052	0.0041	0.0041	0.0156	-1.0696e+03	1.0696e+03	-9.3792e-04	1	462.8661
1	-0.0052	0.0041	0.0195	0.0310	-1.0696e+03	1.0696e+03	-9.3792e-04	1	462.8661
2	-0.0052	0.0041	0.0195	0.0310	-1.0696e+03	1.0696e+03	-9.3792e-04	1	462.8661
3	-0.0052	0.0041	0.0195	0.0310	-1.0696e+03	1.0696e+03	-9.3792e-04	1	462.8661
4	-0.0048	0.0041	-1.6076e-04	0.0109	-717.6878	716.6879	-0.9999	0.6710	432.9410
5	-0.0044	0.0041	-0.0020	0.0087	-336.3103	335.3141	-0.9963	0.3144	397.0429
6	-0.0041	0.0041	-0.0060	0.0042	78.4320	-79.4244	-0.9924	-0.0733	336.0887

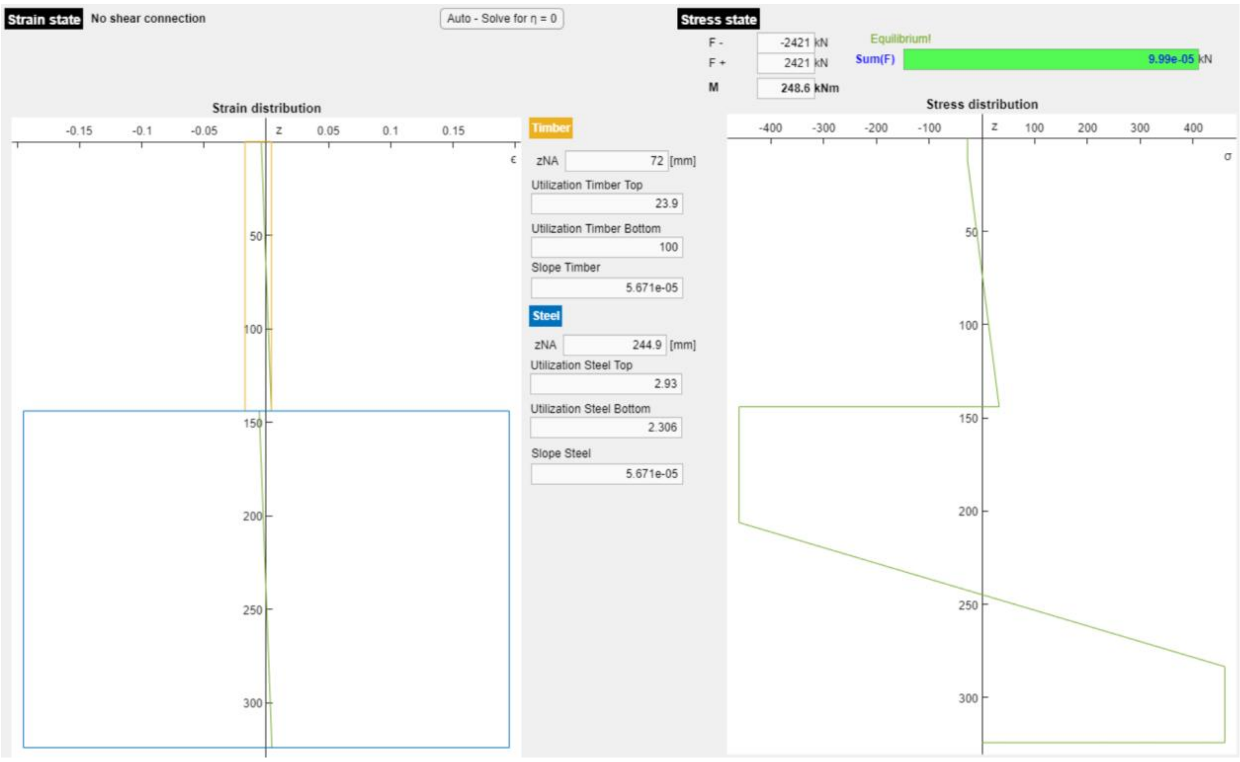


IPE 180, S460, t=1666x144

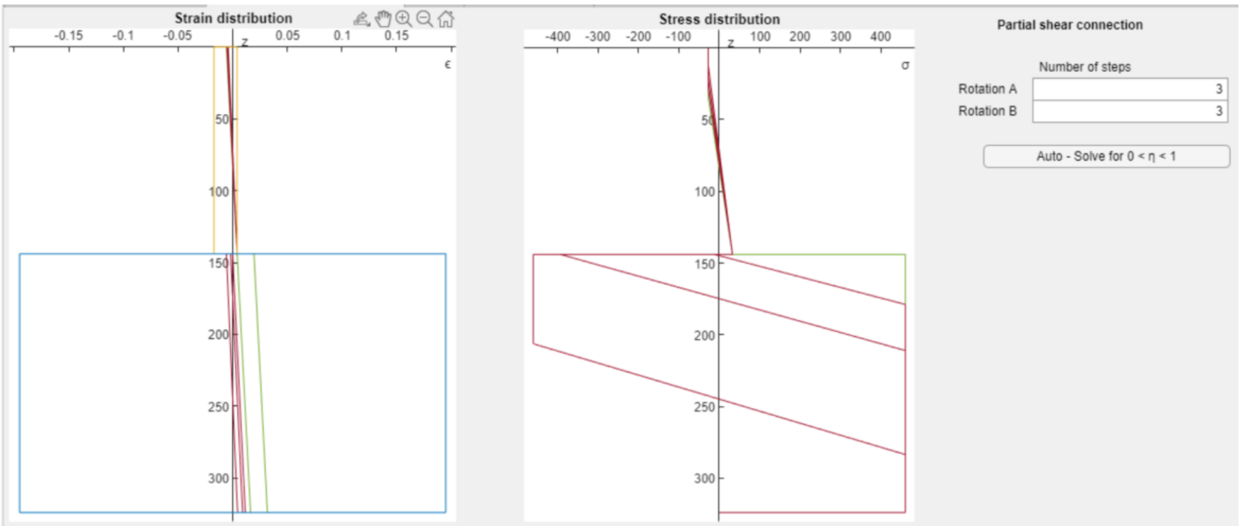
Results for full shear connection:



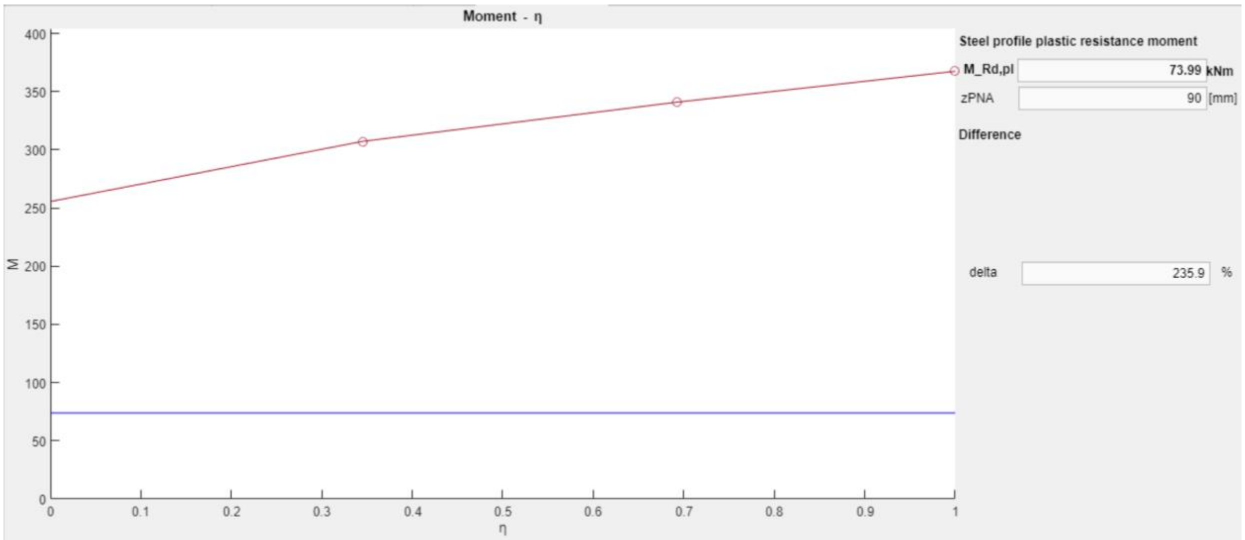
Results for no shear connection:



Results for partial shear connection:

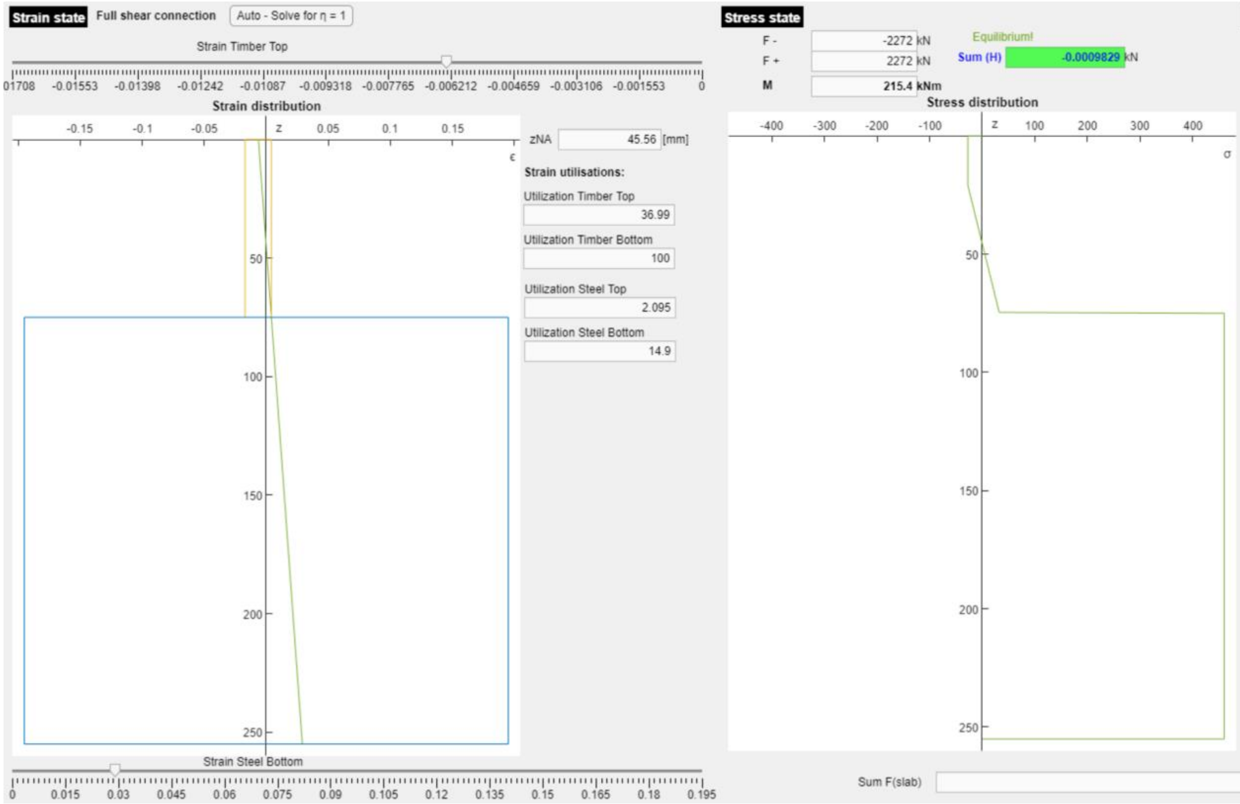


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0058	0.0041	0.0041	0.0164	-1.0696e+03	1.0696e+03	-9.9303e-04	1	367.5352
1	-0.0058	0.0041	0.0195	0.0318	-1.0696e+03	1.0696e+03	-9.9303e-04	1	367.5352
2	-0.0058	0.0041	0.0195	0.0318	-1.0696e+03	1.0696e+03	-9.9303e-04	1	367.5352
3	-0.0058	0.0041	0.0195	0.0318	-1.0696e+03	1.0696e+03	-9.9303e-04	1	367.5352
4	-0.0052	0.0041	-5.7033e-05	0.0115	-740.4957	739.4958	-0.9999	0.6923	340.9758
5	-0.0046	0.0041	-0.0019	0.0090	-369.4408	368.4451	-0.9957	0.3454	307.3375
6	-0.0041	0.0041	-0.0057	0.0045	52.2671	-53.2598	-0.9928	-0.0489	248.3116

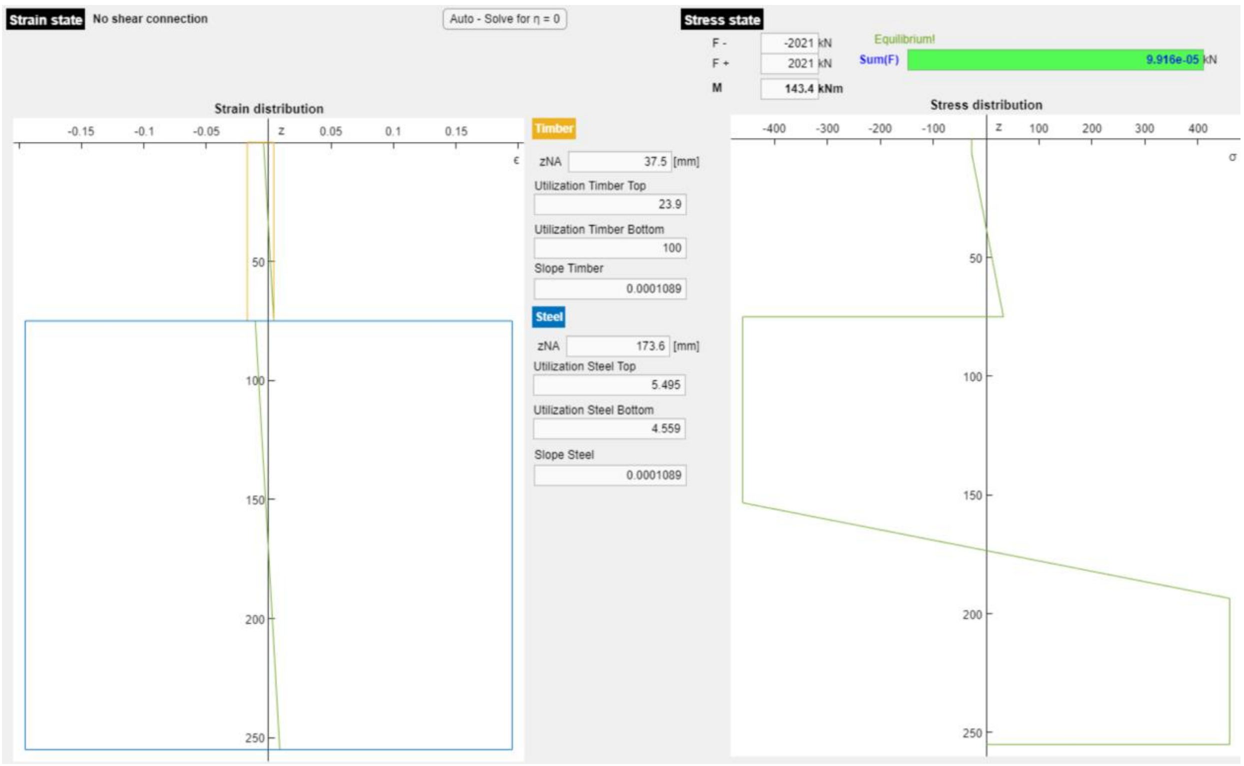


IPE 180, S460, t=2500x75

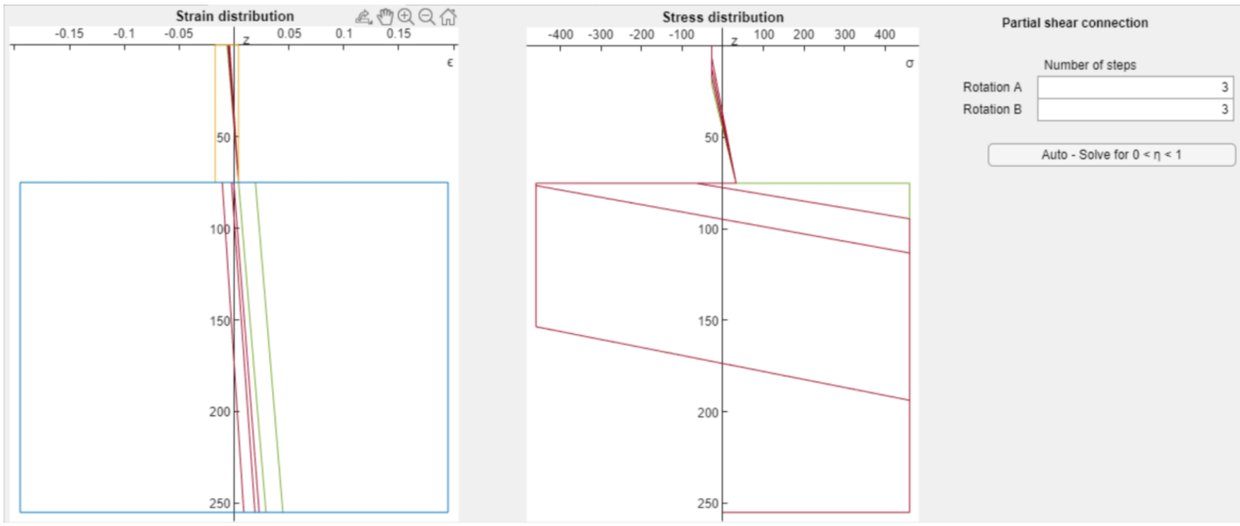
Results for full shear connection:



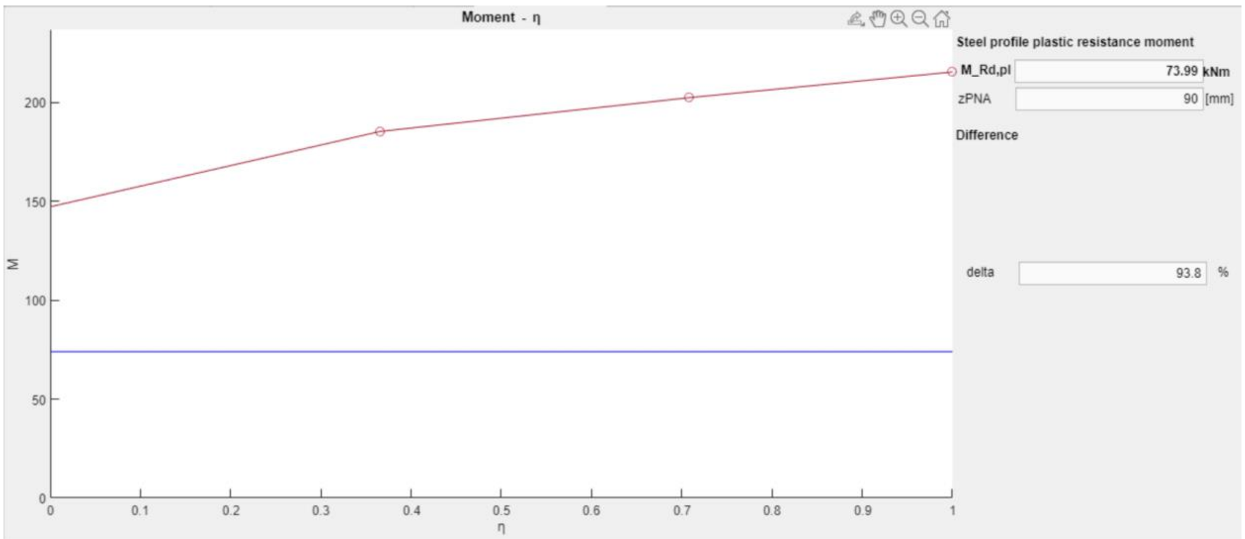
Results for no shear connection:



Results for partial shear connection:

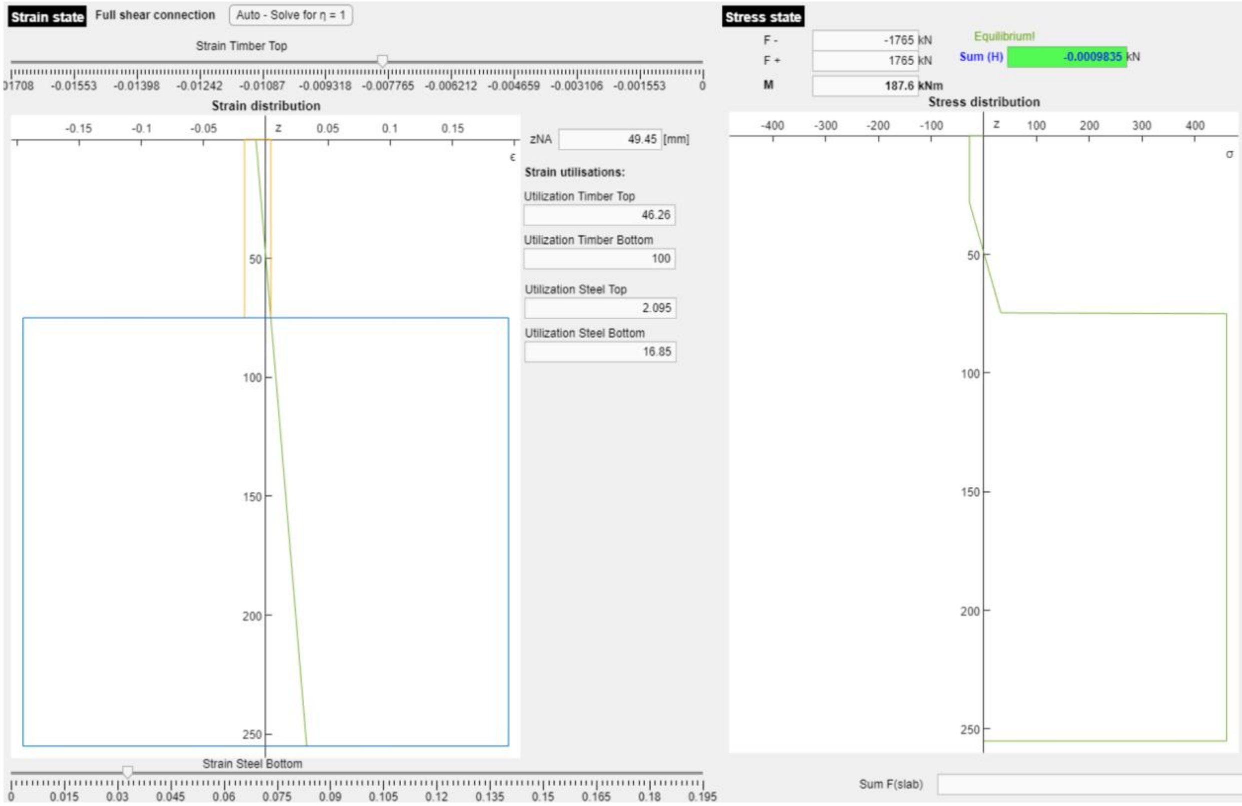


Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0063	0.0041	0.0041	0.0291	-1.0696e+03	1.0696e+03	-9.8287e-04	1	215.3535
1	-0.0063	0.0041	0.0195	0.0445	-1.0696e+03	1.0696e+03	-9.8287e-04	1	215.3535
2	-0.0063	0.0041	0.0195	0.0445	-1.0696e+03	1.0696e+03	-9.8287e-04	1	215.3535
3	-0.0063	0.0041	0.0195	0.0445	-1.0696e+03	1.0696e+03	-9.8287e-04	1	215.3535
4	-0.0056	0.0041	-3.1690e-04	0.0229	-756.5756	755.5768	-0.9989	0.7073	202.3343
5	-0.0048	0.0041	-0.0023	0.0190	-391.2117	390.2150	-0.9967	0.3658	185.3036
6	-0.0041	0.0041	-0.0107	0.0089	40.8500	-41.8389	-0.9889	-0.0382	143.2247

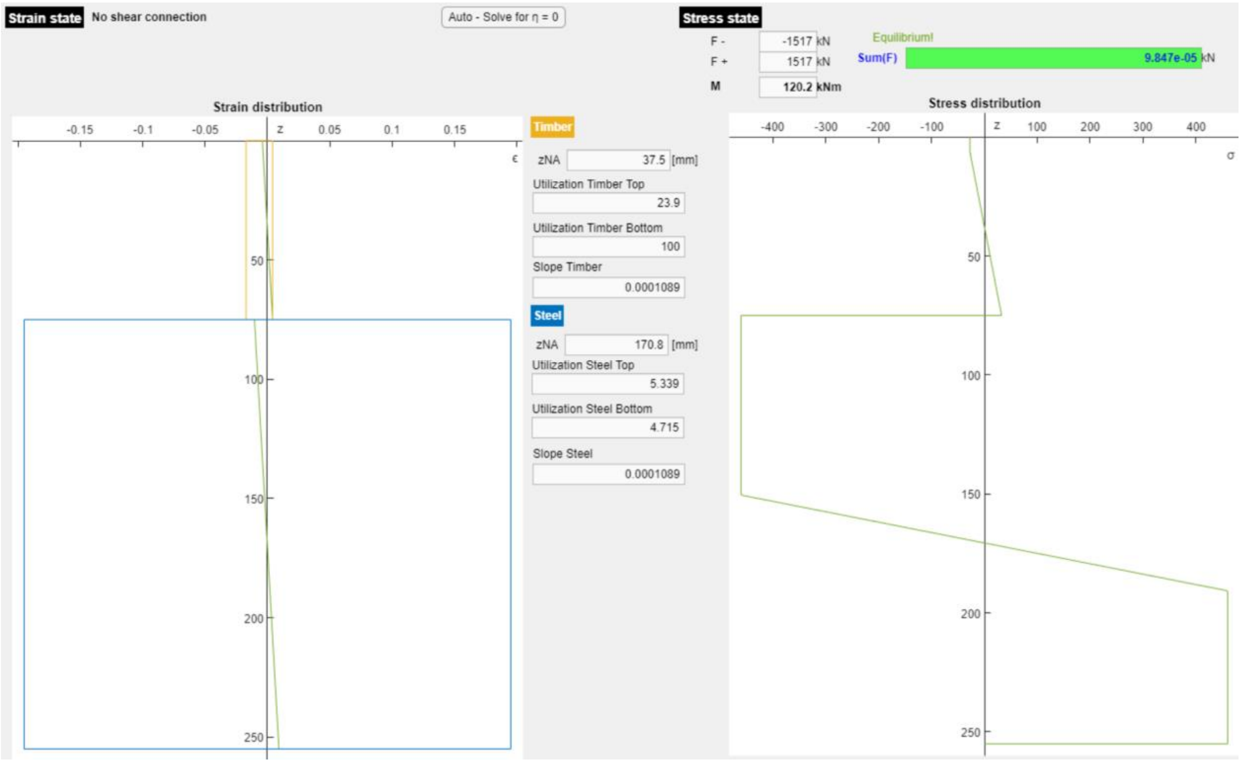


IPE 180, S460, t=1666x75

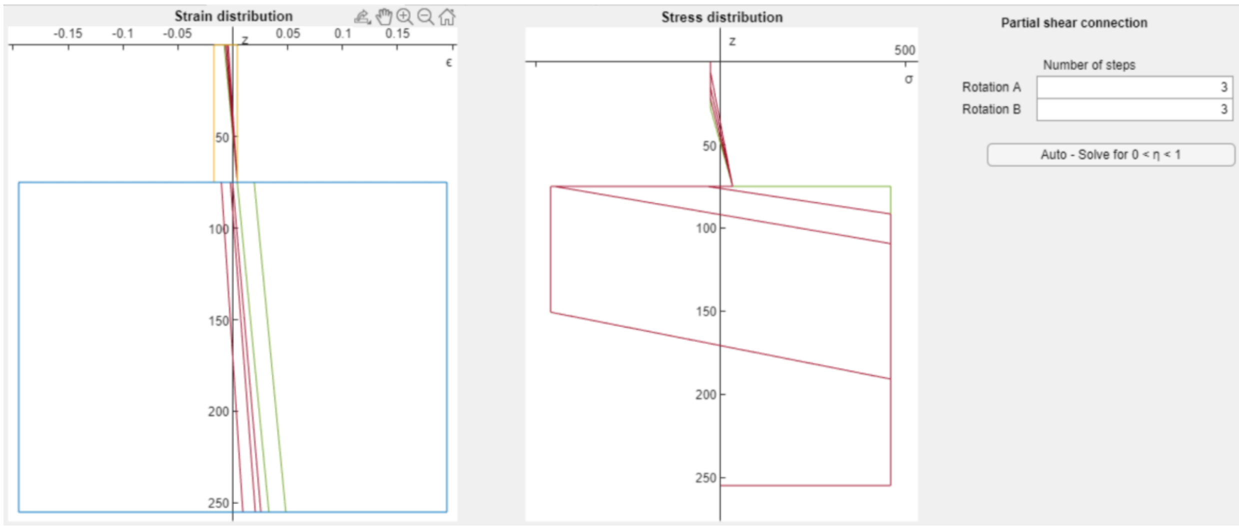
Results for full shear connection:



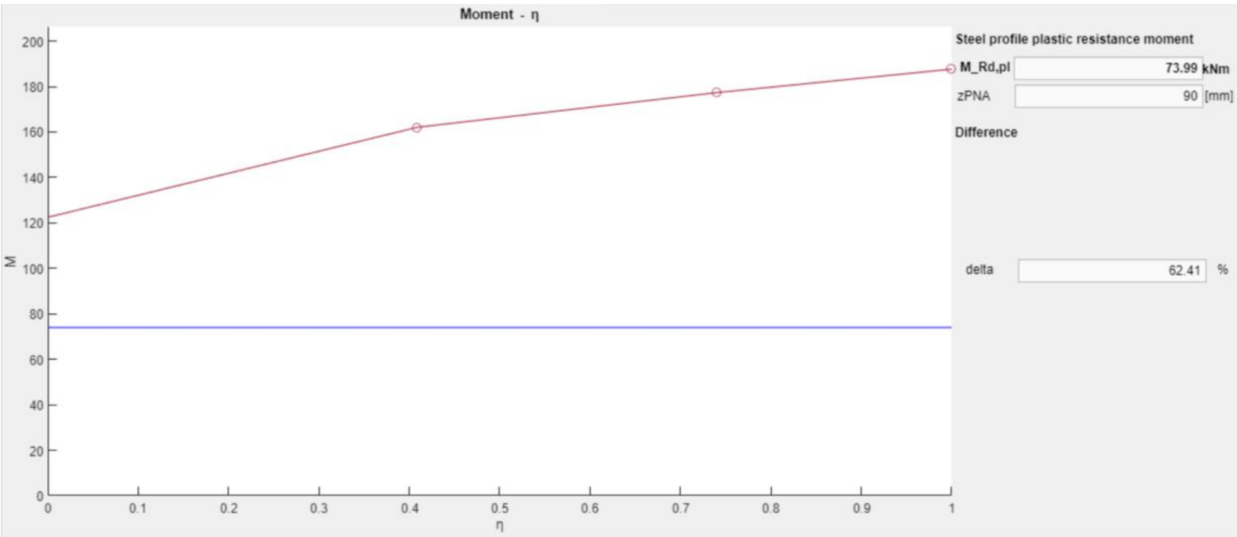
Results for no shear connection:



Results for partial shear connection:

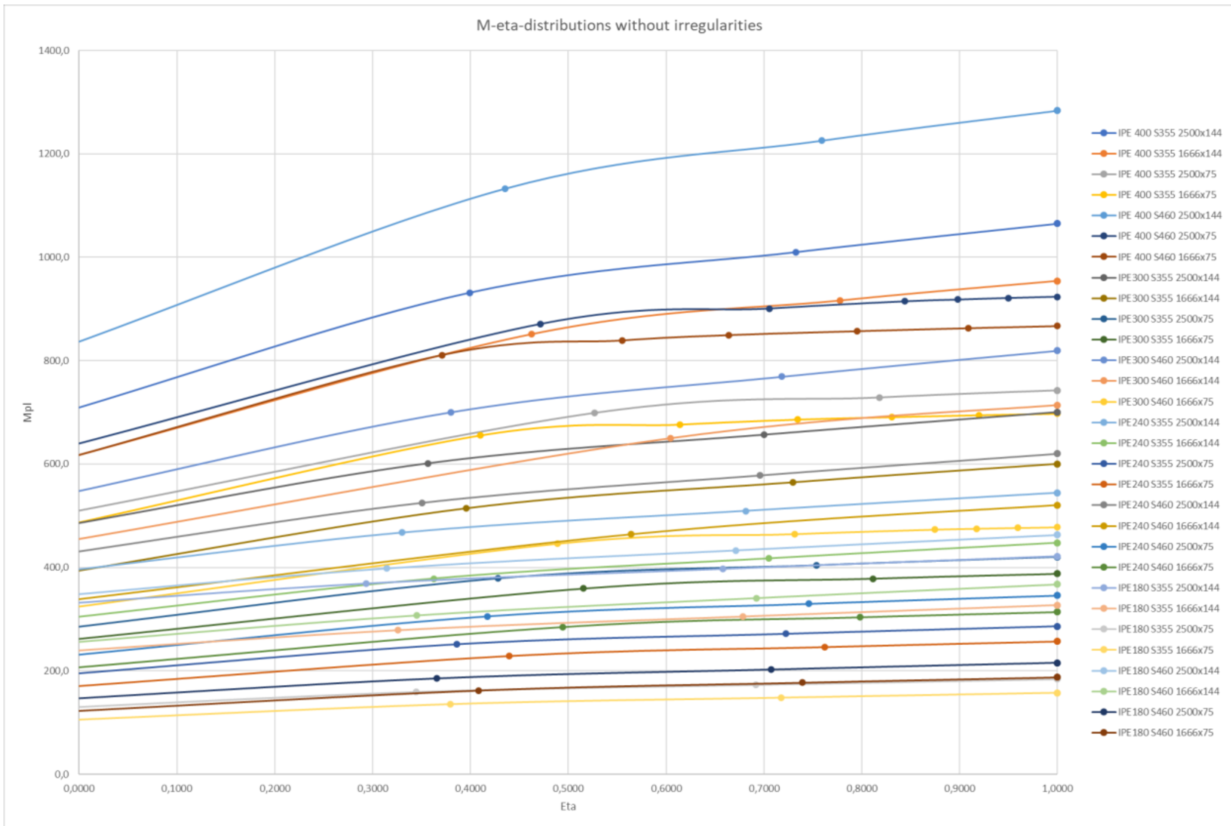


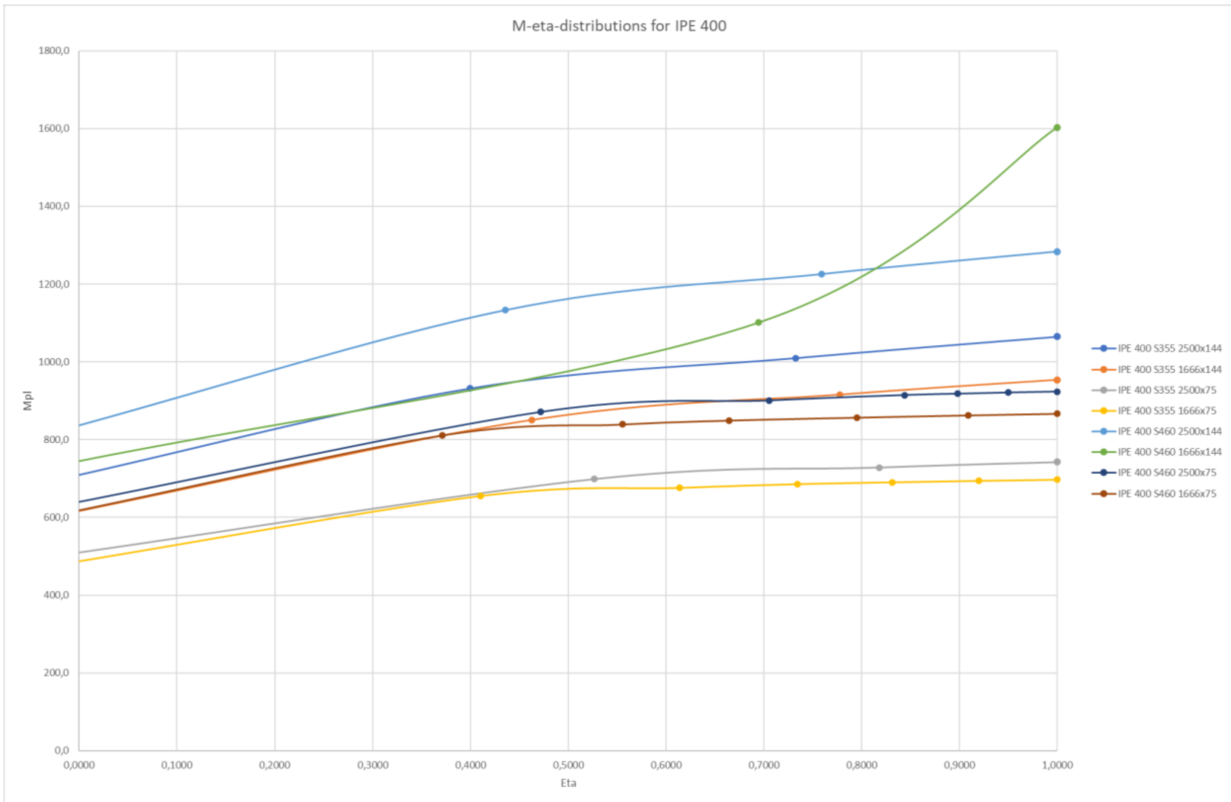
Step	Timber Top	Timber Bottom	Steel Top	Steel Bottom	Force Timber [kN]	Force Steel [kN]	Force Total [kN]	Eta [-]	Moment [kNm]
0	-0.0079	0.0041	0.0041	0.0328	-1.0696e+03	1.0696e+03	-9.8351e-04	1	187.6384
1	-0.0079	0.0041	0.0195	0.0483	-1.0696e+03	1.0696e+03	-9.8351e-04	1	187.6384
2	-0.0079	0.0041	0.0195	0.0483	-1.0696e+03	1.0696e+03	-9.8351e-04	1	187.6384
3	-0.0079	0.0041	0.0195	0.0483	-1.0696e+03	1.0696e+03	-9.8351e-04	1	187.6384
4	-0.0066	0.0041	-1.7246e-04	0.0255	-790.8890	789.8897	-0.9993	0.7394	177.2833
5	-0.0054	0.0041	-0.0021	0.0205	-436.9939	435.9969	-0.9970	0.4086	162.0455
6	-0.0041	0.0041	-0.0104	0.0092	27.2224	-28.2180	-0.9956	-0.0255	120.0015



Annex B

This annex contains further diagrams created based on the parameter study.




M-eta-distributions for IPE 400
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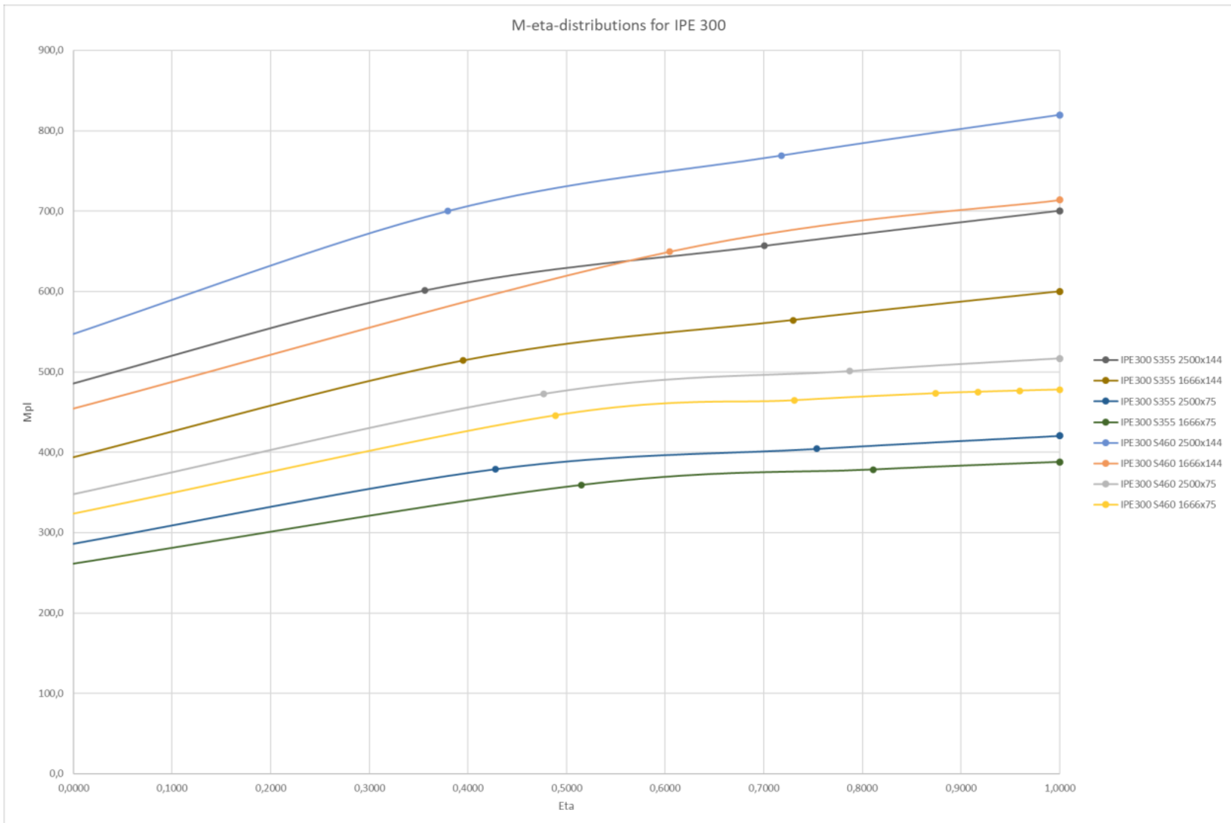
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
Mpl
0,0000
0,1000
0,2000
0,3000
0,4000
0,5000
0,6000
0,7000
0,8000
0,9000
1,0000
Eta
IPE 400 S355 2500x144
IPE 400 S355 1666x144
IPE 400 S355 2500x75
IPE 400 S355 1666x75
IPE 400 S460 2500x144
IPE 400 S460 1666x144
IPE 400 S460 2500x75
IPE 400 S460 1666x75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700,0
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500,0
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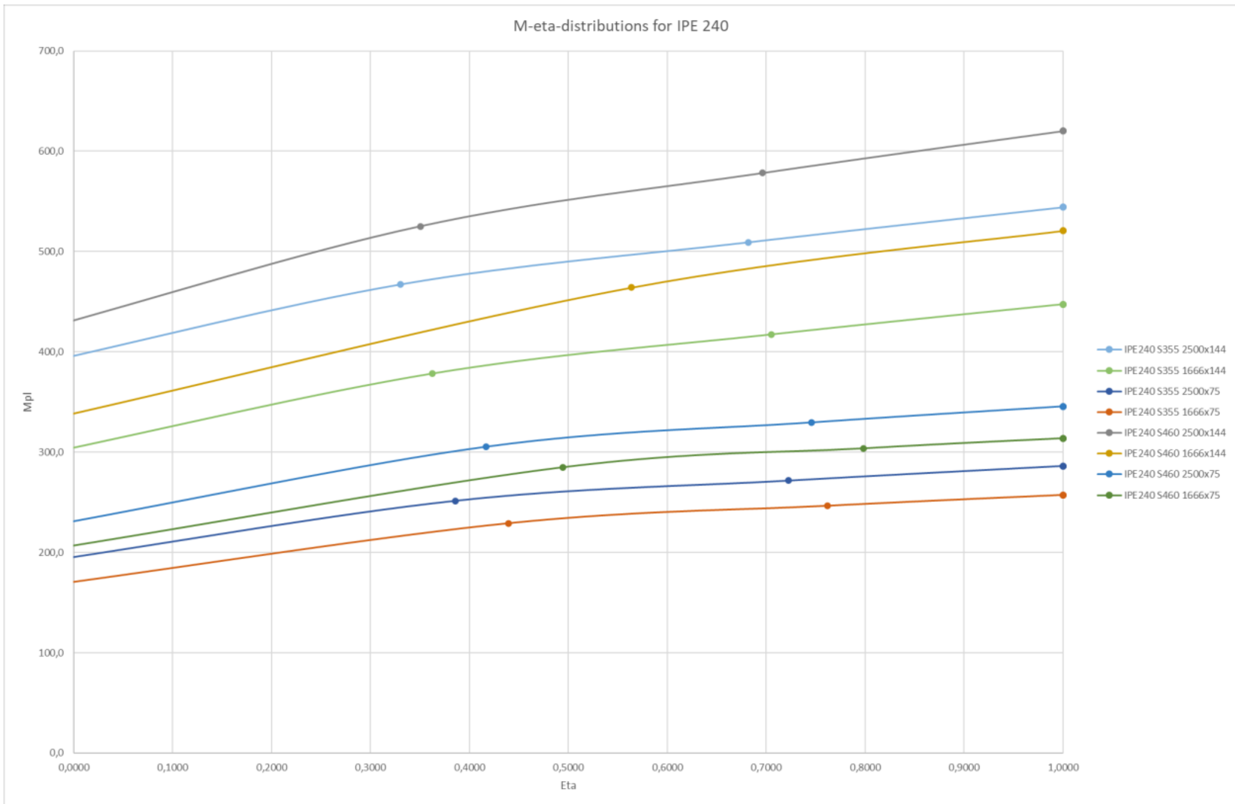
200,0
100,0
0,0
Mpl
0,0000
0,1000
0,2000
0,3000
0,4000
0,5000
0,6000
0,7000
0,8000
0,9000
1,0000
Eta
IPE300 S355 2500x144
IPE300 S355 1666x144
IPE300 S355 2500x75
IPE300 S355 1666x75
IPE300 S460 2500x144
IPE300 S460 1666x144
IPE300 S460 2500x75
IPE300 S460 1666x75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200,0
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Mpl
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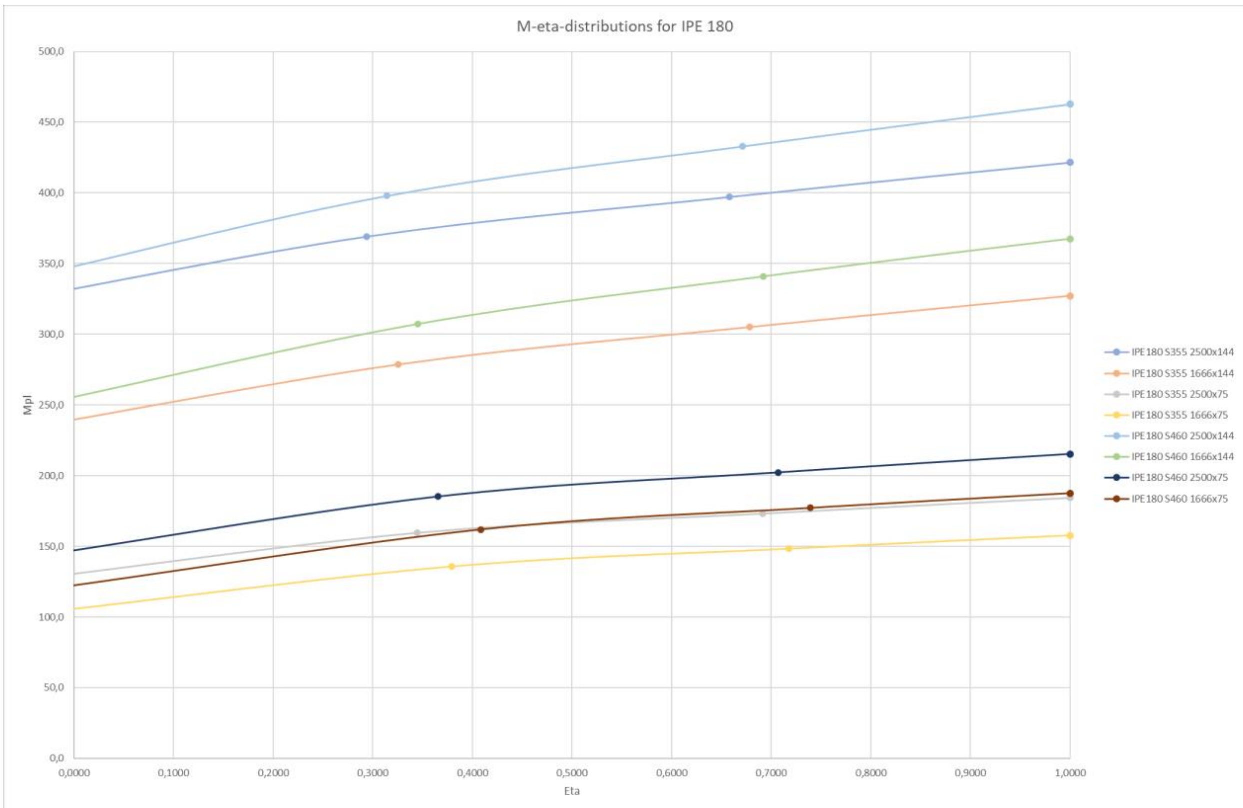
0,5000
0,6000
0,7000
0,8000
0,9000
1,0000
Eta
IPE 240 S355 2500x144
IPE 240 S355 1666x144
IPE 240 S355 2500x75
IPE 240 S355 1666x75
IPE 240 S460 2500x144
IPE 240 S460 1666x144
IPE 240 S460 2500x75
IPE 240 S460 1666x75


M-eta-distributions for IPE 180
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400,0
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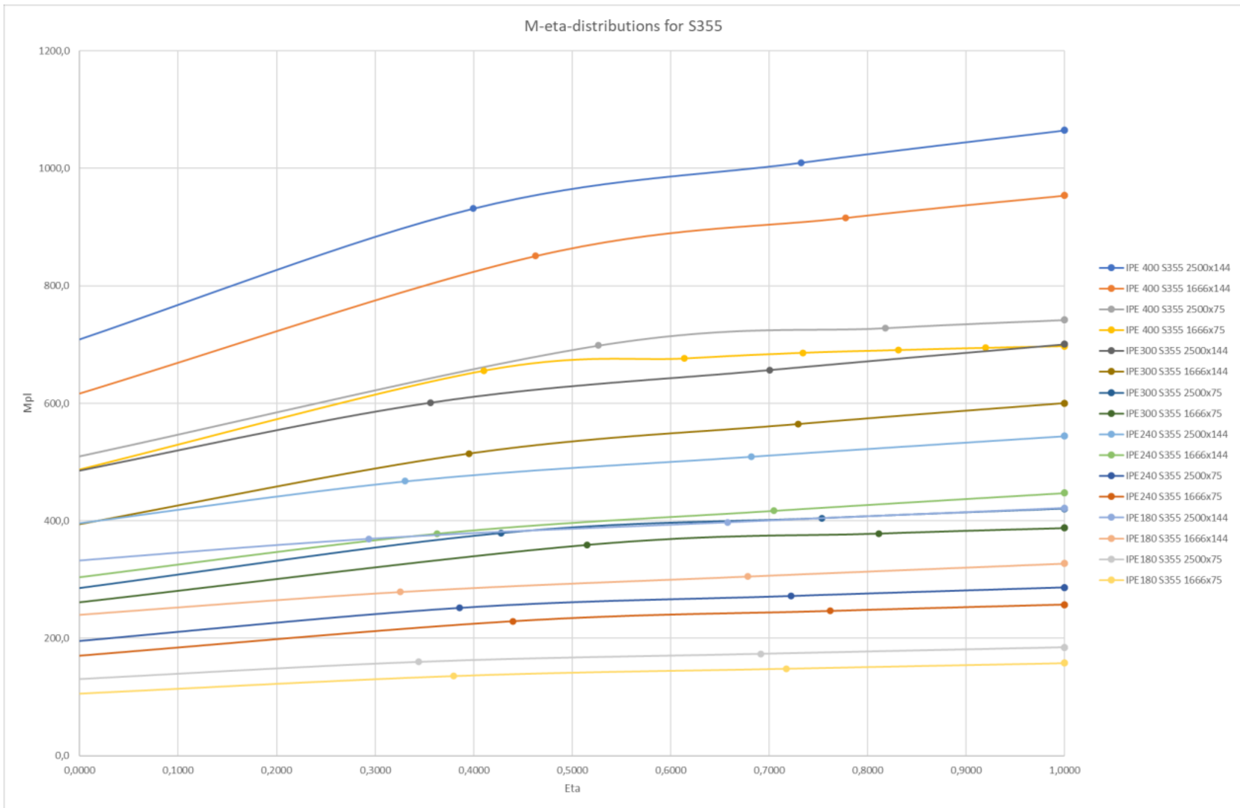
300,0
250,0
200,0
150,0
100,0
50,0
0,0
Mpl
0,0000
0,1000
0,2000
0,3000
0,4000
0,5000
0,6000
0,7000
0,8000
0,9000
1,0000
Eta
IPE 180 S355 2500x144
IPE 180 S355 1666x144
IPE 180 S355 2500x75
IPE 180 S355 1666x75
IPE 180 S460 2500x144
IPE 180 S460 1666x144
IPE 180 S460 2500x75
IPE 180 S460 1666x75


M-eta-distributions for S355
Mpl
Eta
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0,2000
0,3000
0,4000
0,5000
0,6000
0,7000
0,8000
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1,0000
IPE 400 S355 2500x144
IPE 400 S355 1666x144
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IPE 400 S355 1666x75
IPE300 S355 2500x144
IPE300 S355 1666x144
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IPE300 S355 1666x75
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IPE240 S355 1666x144
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IPE180 S355 1666x144
IPE180 S355 2500x75
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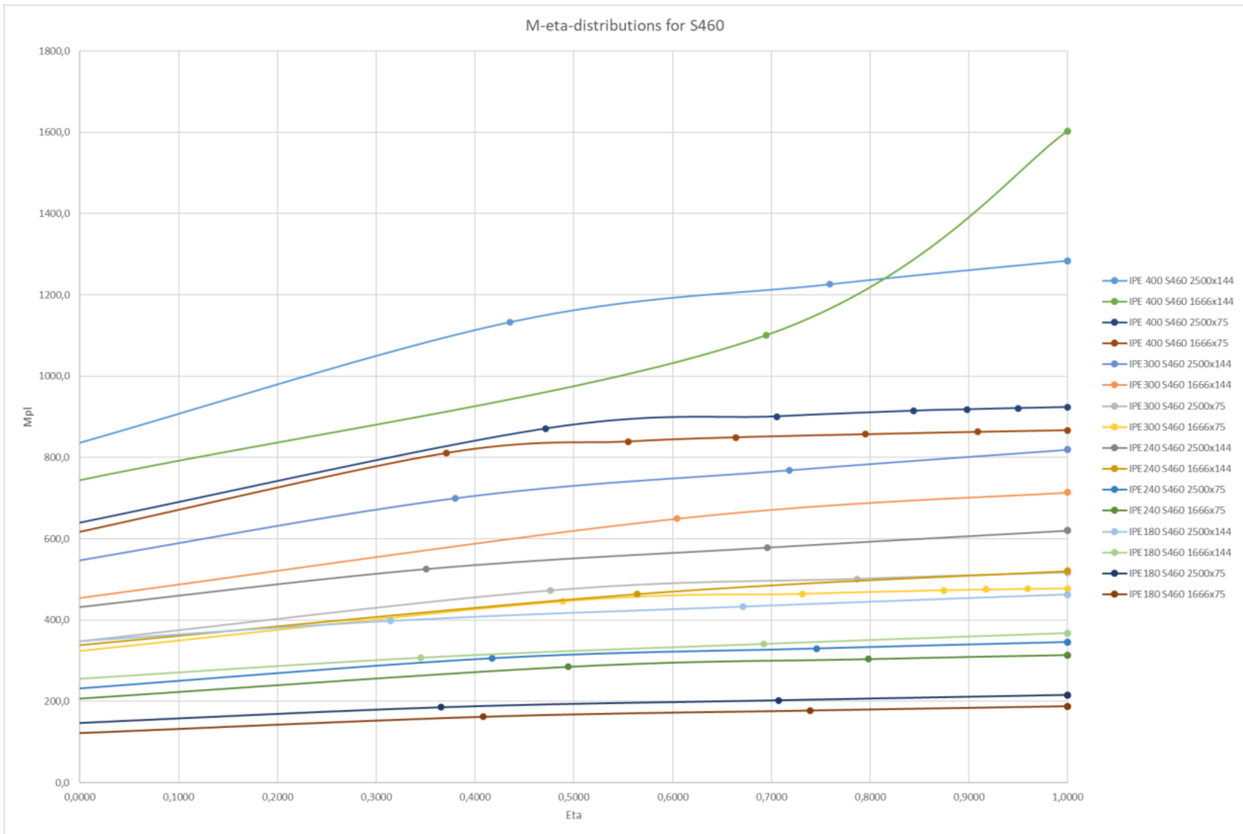
M-eta-distributions for S460
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1,0000
IPE 400 S460 2500x144
IPE 400 S460 1666x144
IPE 400 S460 2500x75
IPE 400 S460 1666x75
IPE300 S460 2500x144
IPE300 S460 1666x144
IPE300 S460 2500x75
IPE300 S460 1666x75
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IPE240 S460 2500x75
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IPE180 S460 2500x144
IPE180 S460 1666x144
IPE180 S460 2500x75
IPE180 S460 1666x75