European Commission
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ANGELHY

Innovative solutions for design and strengthening of telecommunications and transmission lattice towers using large angles from high strength steel and hybrid techniques of angles with FRP strips

WORK PACKAGE 3 – DELIVERABLE 3.1

TECHNICAL SPECIFICATIONS FOR LABORATORY TESTS

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Specifications for laboratory tests on closely spaced built-up members

1 Introduction

Work package WP3 of the project ANGELHY includes 16 laboratory tests on closely spaced built-up members fabricated from angle sections. Three different configurations are to be tested:

1) 6 buckling tests on **back-to-back connected angles** (noted as BBE – see Figure 1 a))
2) 6 buckling tests on **star battened angles with equal sections** (noted as SBE – see Figure 1 b))
3) 4 buckling tests on **star battened angles with unequal sections** (noted as SBU – see Figure 1 c))

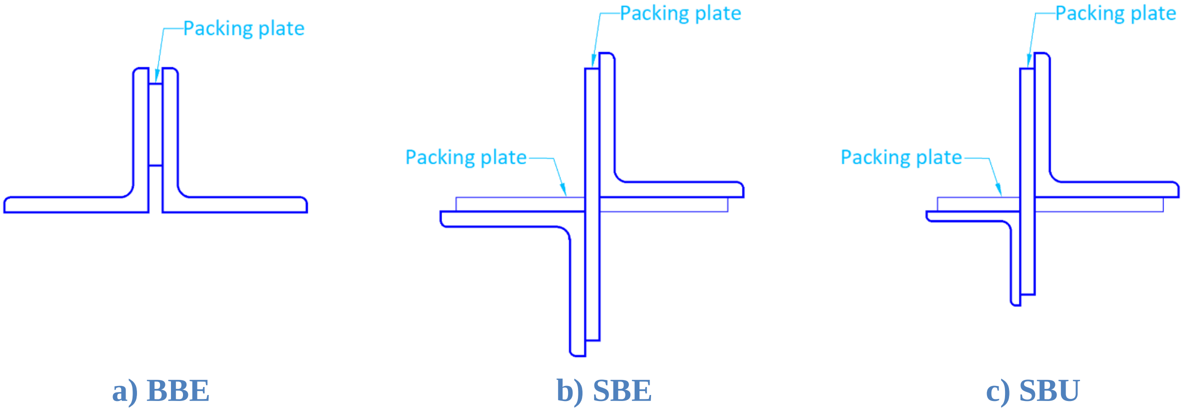


Figure 1: Typology of closely spaced built-up members to be tested

Different member lengths and different spacing distances between packing plates are tested according to Table 1. Depending on the possibilities of delivery, it is intended to test sections fabricated from steel grade **S355 or S460**.

Table 1: Overview of the laboratory tests to be performed

Test	Spacing of packing plates	Member slenderness	Clearance
BBE1	≈ $15i_{min}$	≈ 0,5	No
BBE2	≈ $15i_{min}$	≈ 1,5	No
BBE3	≈ $50i_{min}$	≈ 0,5	No
BBE4	≈ $50i_{min}$	≈ 1,5	No
BBE5	≈ $15i_{min}$	≈ 1,5	Yes
BBE6	≈ $50i_{min}$	≈ 1,5	Yes
SBE1	≈ $60i_{min}$	≈ 0,5	No
SBE2	≈ $60i_{min}$	≈ 1,5	No
SBE3	≈ $90i_{min}$	≈ 0,5	No
SBE4	≈ $90i_{min}$	≈ 1,5	No
SBE5	≈ $60i_{min}$	≈ 1,5	Yes
SBE6	≈ $90i_{min}$	≈ 1,5	Yes
SBU1	≈ $60i_{min}$	≈ 0,5	No
SBU2	≈ $60i_{min}$	≈ 1,5	No
SBU3	≈ $90i_{min}$	≈ 0,5	No
SBU4	≈ $90i_{min}$	≈ 1,5	No
i_{min}: is the minimum radius of gyration of the cross-section angles			

This report describes the design of the laboratory tests to be performed on closely spaced built-up members at University of Liège. A detailed summary of the laboratory tests is given in Paragraph 2.

The choice of the test specimens, the accompanying measurements and the experimental procedure of the laboratory tests are described in Paragraphs 3, 4, 5 and 6 of this report.

2 Summary of the laboratory tests

It should be noted that the specimens have been chosen in Paragraph 3 based on the assumption of a yield strength of **355 MPa (S355)**. The packing plates may be fabricated from lower steel grades.

Table 2: Summary of the laboratory tests

Notation	Cross-section	Member length L (mm)*	Total number of packing plates**	Estimated failure load (kN)	Mid-span displacement for peak load level (mm)
BBE1	2 L 70 x 70 x 7	1200	7	630	1,6
BBE2	2 L 70 x 70 x 7	3600	19	230	34
BBE3	2 L 70 x 70 x 7	2000	4	490	5
BBE4	2 L 70 x 70 x 7	3600	6	220	22
BBE5	2 L 70 x 70 x 7	3600	19	-	-
BBE6	2 L 70 x 70 x 7	3600	6	-	-
SBE1	2 L 60 x 60 x 6	2200	2 x 4	220	15
SBE2	2 L 60 x 60 x 6	3000	2 x 5	130	35
SBE3	2 L 60 x 60 x 6	3000	2 x 4	130	35
SBE4	2 L 60 x 60 x 6	4000	2 x 5	80	70
SBE5	2 L 60 x 60 x 6	3000	2 x 5	-	-
SBE6	2 L 60 x 60 x 6	4000	2 x 5	-	-
SBU1	L 80 x 80 x 8 + L 60 x 60 x 6	2200	2 x 4	260	1,9
SBU2	L 80 x 80 x 8 + L 60 x 60 x 6	3000	2 x 5	200	2,3
SBU3	L 80 x 80 x 8 + L 60 x 60 x 6	3000	2 x 4	200	2,9
SBU4	L 80 x 80 x 8 + L 60 x 60 x 6	4000	2 x 5	140	2,8

*The total length of the angles should be sufficient to extract material for the tensile tests and to measure geometric cross-section dimensions (L_{tot} = L+4000mm)
**Including packing plates at the supports

For each test series (BBE, SBE and SBU), the testing procedure, described in the following paragraphs, is to be validated by means of one preliminary test on specimens BBE6, SBE5 and SBU2. Consequently, specimens BBE6, SBE5 and SBU2 have to be fabricated twice.
These preliminary tests are performed following the test procedure provided in Paragraph 5 and respecting the design of the test rig represented in Paragraph 6. The outcome of the preliminary tests allows the adjustment of the testing procedure if necessary.

3 Choice of test specimens

3.1 General

Before the test specimens may be designed, it is necessary to recall the principal limitations of the used testing rig:

- Maximum length of the tested members: 4 m;
- Maximum failure load: 300 t (=3000 kN).

Additionally, it is to be noted that **at least two intermediate packing plates** have to be used in order to study their influence on the buckling resistance of the built-up member. So as to represent the practical habit, only angles of section L60x60x6 and greater are considered for the laboratory tests.
Last, it is intended to use the same cross-section for each typology of member (BBE, SBE and SBU) so as to limit the parameters that are varied in the laboratory tests.
The choice of the test specimens is based on two steps. First, the specimens are chosen based on simplified assumptions. Then numerical simulations are performed to confirm the choice and in order to obtain an estimation of the failure load. The numerical simulations are detailed in Annex A of this report.

3.2 Preliminary design of test specimens

3.2.1 Choice of tests specimens of type BBE

In order to study the influence of the shear stiffness reduction resulting from the bolted connections through the packing plates, the intended failure mode for these tests is buckling about the z-z axis (see Figure 2 for the definition of axis). As the z-z axis corresponds to the major-axis for this type of section, it is necessary to design suitable support conditions in order to reduce the buckling length about the minor-axis. Consequently, the support should be designed as fixed about the minor-axis and pinned about the major-axis (see paragraph 6.2.1 for the design of the support conditions). By doing so, the failure mode corresponds either to flexural buckling about the z-z axis or to buckling of the chords (if the distance between the packing plates was sufficiently high).

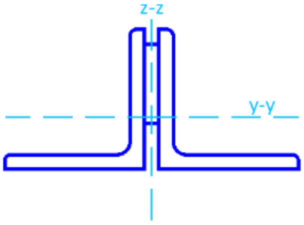


Figure 2 : System of axes for BBE specimens

The choice of the sections is based on the simplified assumption that the member acts as a whole, neglecting the shear flexibility independently from the distance between the packing plates. Based on this assumption, the member lengths corresponding to a relative slenderness of 1,5 are given in Table 3. This table indicates that only members of section L 70 x 70 x 7 and L 60 x 60 x 6 are suitable due to the limitation of the member lengths (L ≤ 4 m).

Table 3: Member lengths of BBE specimens possessing a relative slenderness of 1,5

Cross-section of one chord	Steel grade	Length for λ_z = 1,5 (m)
L 60 x 60 x6	S355	3088
L 70 x 70 x7	S355	3603
L 80 x 80 x 8	S355	4124

Here, cross-section L 70 x 70 x 7 is chosen. The resulting parameters for the six laboratory tests concerning BBE specimens are directly given in Table 4.

Table 4: Parameters for laboratory tests on BBE specimens

Notation	Section	Number of intermediate packing plates	Distance between packing plates (mm)	Total member length (mm)	Member slenderness λ_z
BBE1	L 70 x 70 x 7	5	171 (=12,6i_{min})	1200	0,50
BBE2	L 70 x 70 x 7	17	190 (=14,0i_{min})	3600	1,50
BBE3*	L 70 x 70 x 7	2	608 (=44,7i_{min})	2000	0,95
BBE4	L 70 x 70 x 7	4	685 (=50,4i_{min})	3600	1,50
BBE5**	L 70 x 70 x 7	17	190 (=14,0i_{min})	3600	1,50
BBE6**	L 70 x 70 x 7	4	685 (=50,4i_{min})	3600	1,50

*The length of specimen BBE3 is determined by the minimum number of 2 intermediate packing plates.
**Tests performed with a bolt hole clearance of 2 mm.

3.2.2 Choice of test specimens of type SBE

The choice of the test specimens of type SBE is directly determined by the distance between the packing plates. Indeed, in order to respect the length limitation of 4 m, only specimens of cross-section L 60 x 60 6 are suitable for the chosen field of parameters. The tests are detailed in Table 5 (Again, the member slenderness is calculated without considering the shear flexibility of the built-up member). It should be noted that the failure is characterized by flexural buckling (FB). The torsional buckling mode is less relevant for the studied member lengths as the critical axial force for flexural-torsional buckling is always higher than the one linked to flexural buckling.

Table 5: Parameters for laboratory tests on SBE specimens

Notation	Section	Number of intermediate packing plates	Distance between packing plates (mm)	Total member length (mm)	Member slenderness λ_{FB}
SBE1	L 60 x 60 x 6	2	733 (=62,7i_{min})	2200	1,13
SBE2	L 60 x 60 x 6	3	750 (=64,1i_{min})	3000	1,55
SBE3	L 60 x 60 x 6	2	1000 (=85,5i_{min})	3000	1,55
SBE4	L 60 x 60 x 6	3	1000 (=85,5i_{min})	4000	2,06
SBE5*	L 60 x 60 x 6	3	750 (=64,1i_{min})	3000	1,55
SBE6*	L 60 x 60 x 6	3	1000 (=85,5i_{min})	4000	2,06

*Tests performed with a bolt hole clearance of 2 mm.

3.2.3 Choice of test specimens of type SBU

As for the specimens SBE choice of the section is directly determined by the distance between the packing plates. In order to respect the length limitation of 4 m, only specimens of cross-section L 60 x 60 6 are suitable as smaller chords for SBU built-up members. The taller chord is chosen to obtain a significant member slenderness (for flexural buckling) for the longest specimen. Again, the torsional buckling mode is not significant for the tested member lengths.

Table 6: Parameters for laboratory tests on SBU specimens

Notation	Section	Number of intermediate packing plates	Distance between packing plates (mm)	Total member length (mm)	Member slenderness λ_{FB}
SBU1	L 60 x 60 x 6 + L 80 x 80 8	2	733 (=62,7i_{min})	2200	1,03
SBU2	L 60 x 60 x 6 + L 80 x 80 8	3	750 (=64,1i_{min})	3000	1,40
SBU3	L 60 x 60 x 6 + L 80 x 80 8	2	1000 (=85,5i_{min})	3000	1,40
SBU4	L 60 x 60 x 6 + L 80 x 80 8	3	1000 (=85,5i_{min})	4000	1,87

4 Measurements to be performed before and during a laboratory test

4.1 Preparatory measurements

At least one tensile test should be performed on each tested angle section according to the standard NF EN ISO 6892-1 in order to obtain detailed information concerning the material law to be used for the numerical simulations of the laboratory tests. The tensile test coupon should be located according to EN 10025-1 as represented in Figure 3.

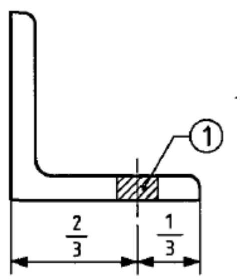
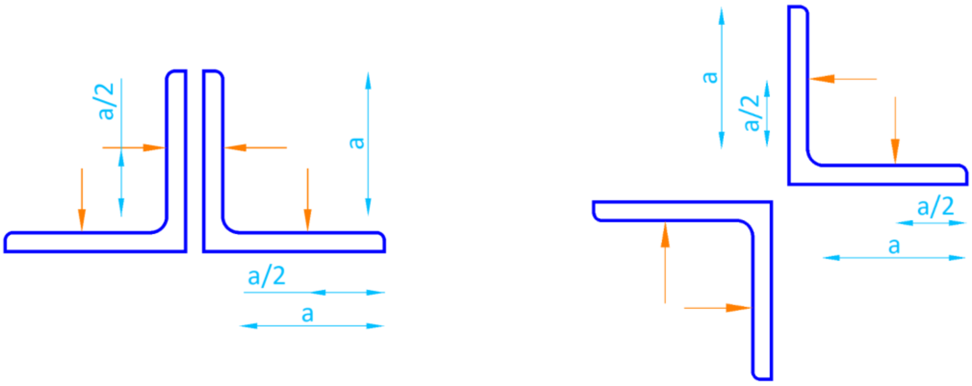


Figure 3: Location of tensile coupon for angle section according to EN 10025-1

Also, the real geometric dimensions of each angle sections should be measured at least 6 times along the member length. In particular, the **height and the thickness of each leg** of the angle section should be reported at the six points of measure.

Finally, the geometric imperfection of the built-up member should be measured. As far as possible, the tolerances should be measured for the member placed in the testing rig. In order to possess sufficient information for the numerical model and the simulations to be performed, the geometric imperfection should be measured at least 6 times along the member length according to Figure 4. In this figure the points of measurements are represented by the orange arrows. Based on these measurements it is possible to determine the initial vertical and lateral imperfection as well as the torsional twist imperfection.



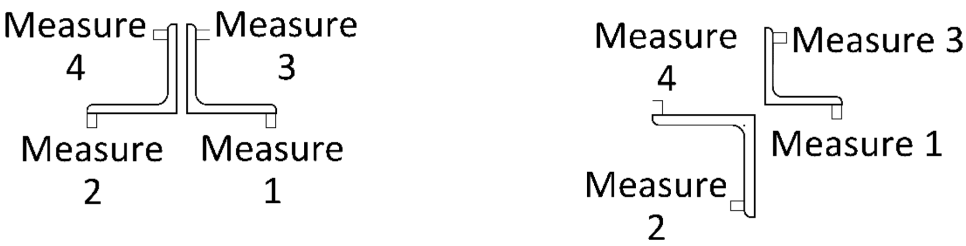
a) BBE specimens **b) SBE specimens**

Figure 4: Points of imperfection measure for test specimens

The obtained data should be transferred to CTICM in a format that may be easily exploited as for example Excel spreadsheets.

4.2 Measurements during an ongoing laboratory test

In order to analyse the behaviour of the tested specimens in detail and to validate that the numerical model represents the observed behaviour, displacements and the evolution of the strain in the cross-section has to be recorded.
Displacements should be measured at mid-height of the member according to Figure 5. These measurements give relevant information about the displacements about both axis and the torsional twist. Also, it is possible to determine whether the built-up member behaves uniformly or if the chords act independently. The laboratory is free to choose the adequate technique to measure the displacements.



a) Location of LVDT for BBE specimens b) Location of LVDT for SBE and SBU specimens

Figure 5: Measurement of displacement of the built-up member at mid-span

The evolution of strains in the built-up member is measured at three intermediate sections corresponding to an abscissa along the member of L/4, L/2 and 3/4L (L is the member length). The strains are to be recorded by strain gauges applied near the tips of each leg as represented in Figure 6 for the example of a SBU specimen. Consequently, twelve strain gauges have to be used of each test.

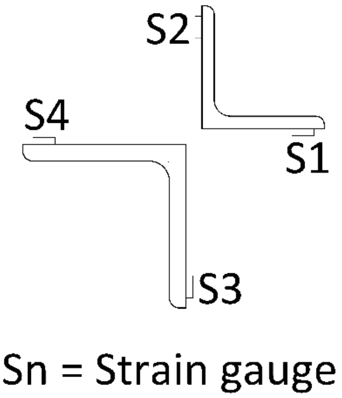


Figure 6: Application of strain gauges

As for the preparatory measurements, the data recorded during the laboratory tests should be transferred to CTICM in a format that may be easily exploited as for example Excel spreadsheets.

5 Test procedure

After installation of the specimens in the testing rig, the initial geometric imperfection of the built-up member should be measured according to paragraph 4.1. Additionally, the exact position of the supports with reference to its theoretical position (see paragraph 6) should be measured in order to record possible eccentricities inducing a supplementary bending moment. After recording of the imperfections, the laboratory test is to be performed in several steps as described below:

1) Load step 1: the axial force is increased by an imposed axial displacement up to an axial force of approximatively 20% of the estimated failure load. The behaviour of the built-up member is completely linear and elastic up to the end of load step 1.
2) Unloading of the member: the imposed displacement is released until the measured reaction force attains approximatively 10% of its value at the end of load step 1.
3) Load step 2: the axial force is increased again by imposing an axial displacement up to the end of the test. The test should be stopped if the reaction force has decreased to 90% of the maximum measured reaction force or if the displacement measured at mid-span has doubled with reference to the same displacement measured at the peak load level.

The loading rate for load step 1 and 2 should be sufficiently small so that the experimental test can be considered as static. The exact loading rate is to be chosen by the laboratory.

Table 7: Load steps for the laboratory tests

Notation	Axial force for load step 1 (kN)
BBE1	125
BBE2	50
BBE3	100
BBE4	50
BBE5	40
BBE6	40
SBE1	45
SBE2	25
SBE3	25
SBE4	20
SBE5	25
SBE6	20
SBU1	50
SBU2	40
SBU3	40
SBU4	30

6 Preliminary design of test rig

6.1 General

Hereafter, the design of the laboratory tests is detailed. The cases of back-to-back connected angle sections (BBE specimens) and star battened angle sections (SBU and SBE specimens) are distinguished because different support conditions have to be designed in order to ensure the intended failure modes.
The packing plates are bolted with structural bolts (nominally not preloaded), independently from the test typology (SBE, SBU or BBE). Nonetheless, in order to avoid the loosening of the connection and to control the exact force in the bolt, the bolts should be preloaded with a force of:

$$0{,}5 \times 0{,}7 \times f_{yb} A_s$$

The bolts used for the packing plate connections should be of class 8.8. The diameter of the bolts is detailed, depending on the test, in the following paragraphs.

6.2 BBE specimens

6.2.1 Support conditions

As stated in paragraphs 3.2 it is necessary to adapt the support conditions for BBE specimens in order to ensure a failure mode characterised by buckling about the major-axis. This buckling mode may be achieved by creating a pinned support about the major-axis and a fixed support about the minor-axis. The following figures represent the design of the supports for BBE specimens. It is to be noted that the packing plates are not represented in Figure 7 to Figure 10.

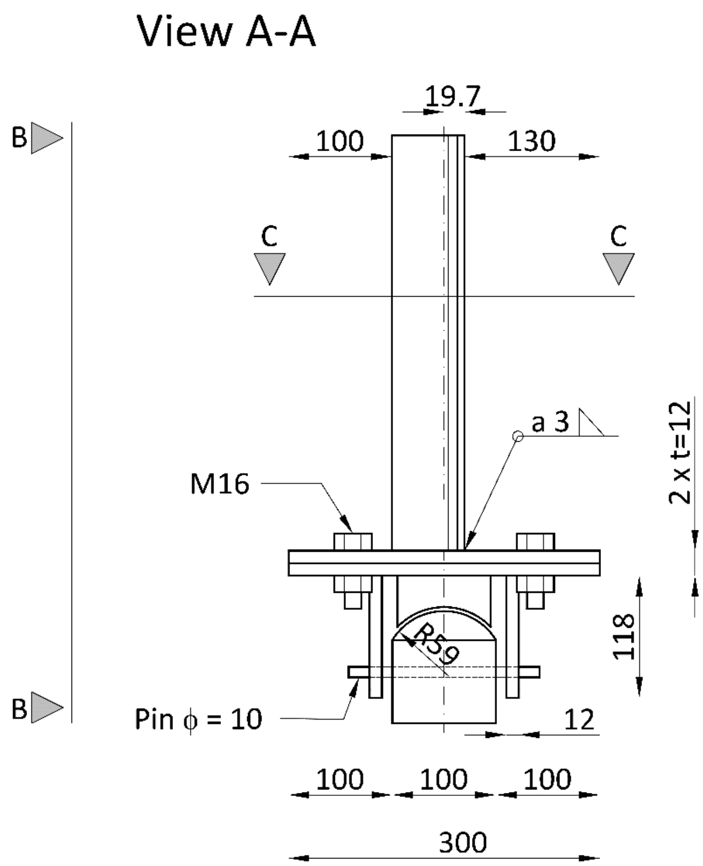


Figure 7 : Side view of support condition – BBE specimen

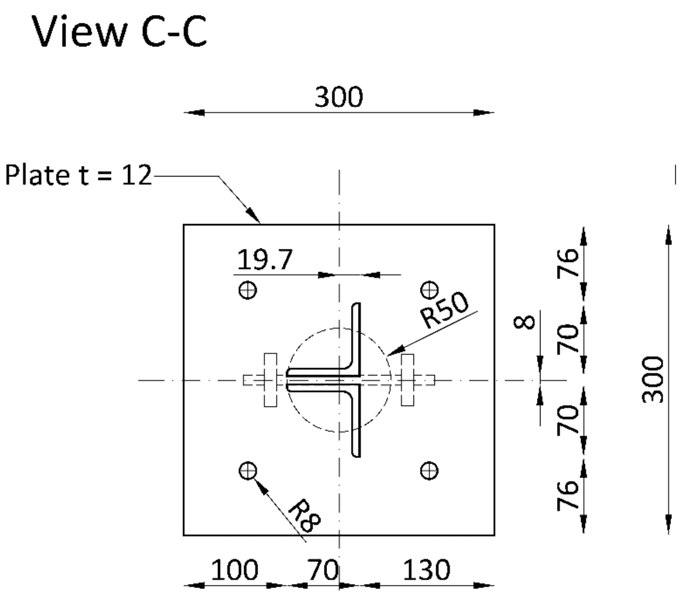


Figure 8 : Plan 1 of support condition – BBE specimen

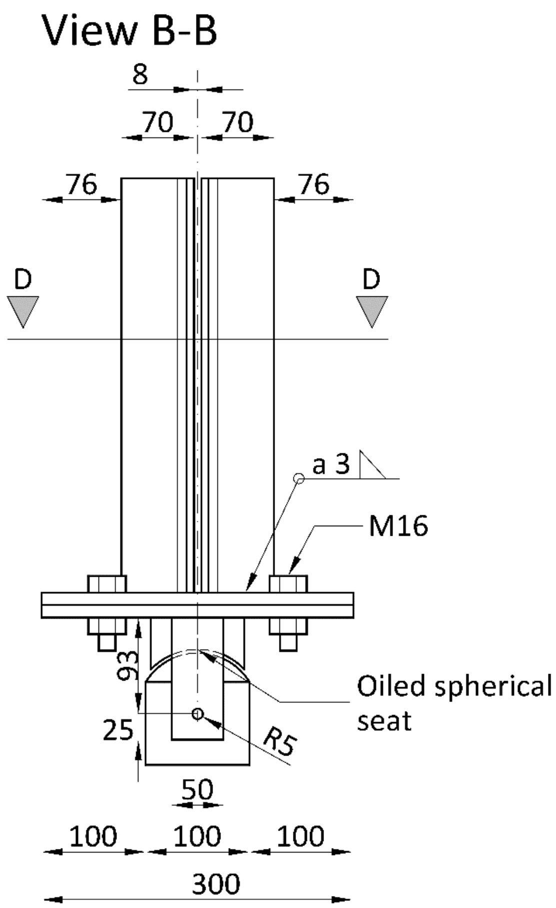


Figure 9 : Front view of support conditions – BBE specimen

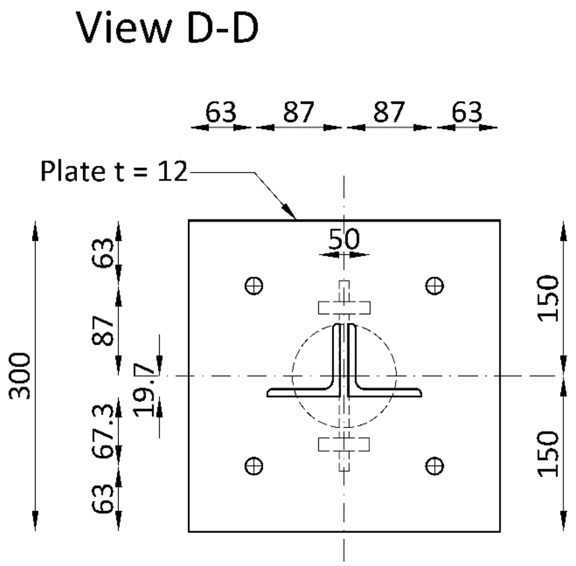
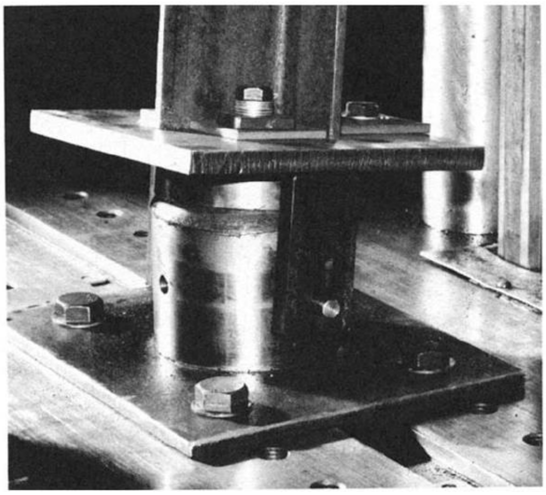
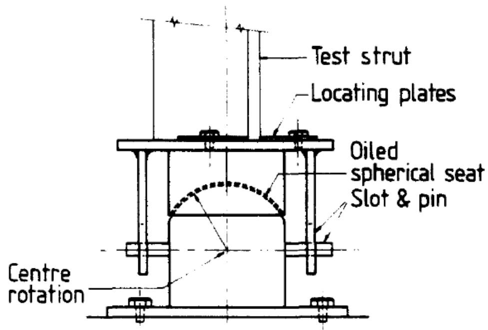


Figure 10 Plan 2 of support conditions – BBE specimen

A similar test arrangement has been applied in reference (Kitipornchai et al. 1986) as represented in Figure 11.





a) Photo of ongoing test **b) Schematic view of support conditions**

Figure 11 : Support conditions designed in reference (Kitipornchai et al. 1986)

A different design of the support conditions may be accepted if it ensures the fixed condition about the minor-axis of the built-up member. In this case, the laboratory transmits the detailed plans of the supports to CTICM.

6.2.2 Packing plate connection

Specimens BBE are connected by one single bolt. For specimens BBE1 to BBE4 fit bolts should be used in order to exclude clearance of the bolt holes. Specimens BBE5 and BBE6 explicitly include a bolt hole clearance.

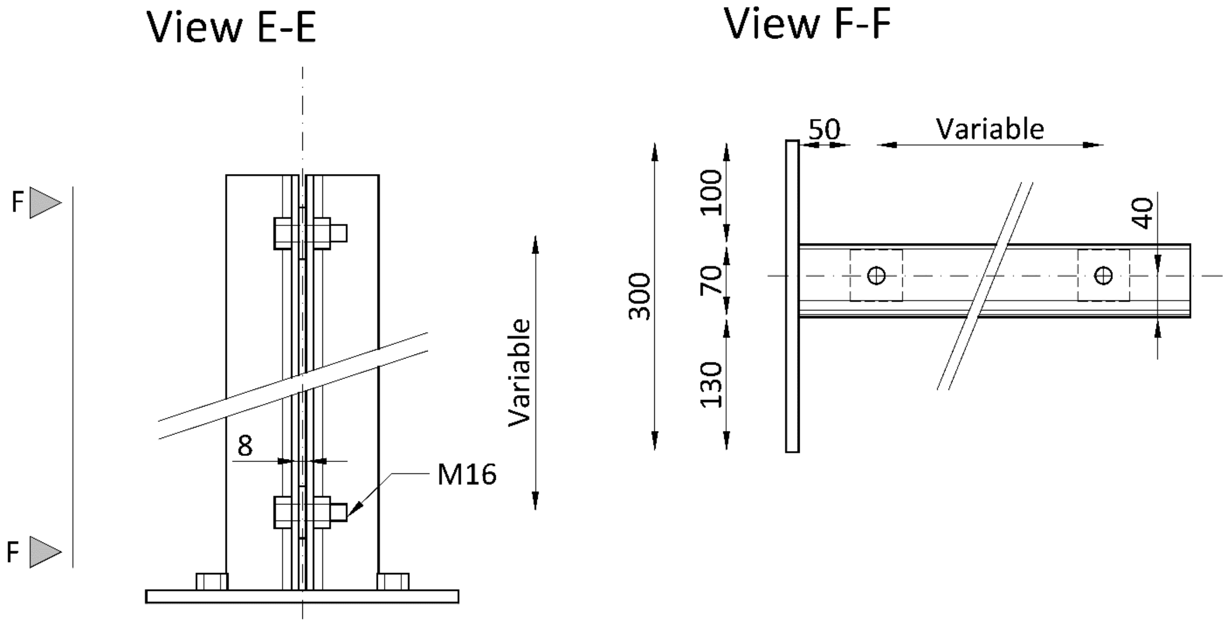
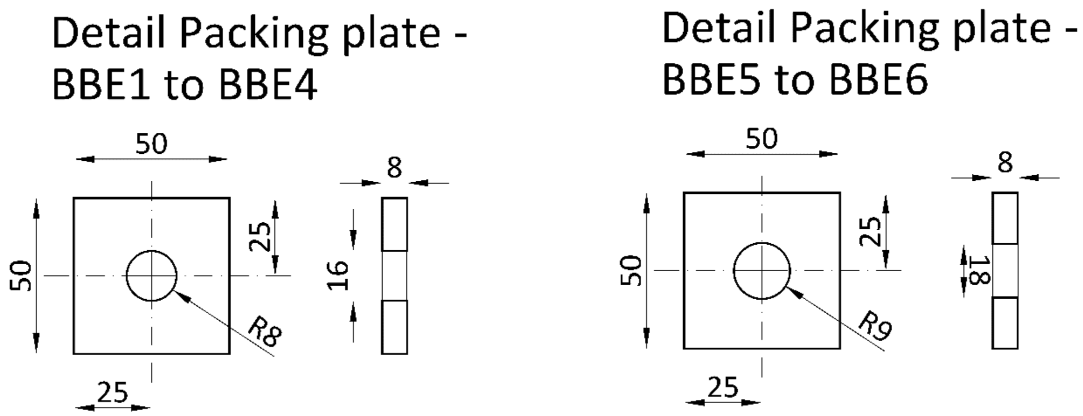


Figure 12 : Packing plate connection – BBE specimen



a) Packing plates without bolt hole clearance **b) Packing plates with bolt hole clearance**

Figure 13: Detail of packing plates – BBE specimen

6.3 SBE specimens

6.3.1 Support conditions

The support conditions are designed similarly to the case of BBE specimens. Conversely to the back-to-back connected angle sections, the plane of buckling is not imposed for SBE specimens. Accordingly, the pin (see Figure 7) is not used. For SBE specimens, the loading sphere is situated under the theoretical centre of gravity of the built-up member. Consequently, the SBE specimens are exclusively subject to a first order axial force.
The following figures show the details of the support conditions for SBE. Again, the packing plates are not represented.

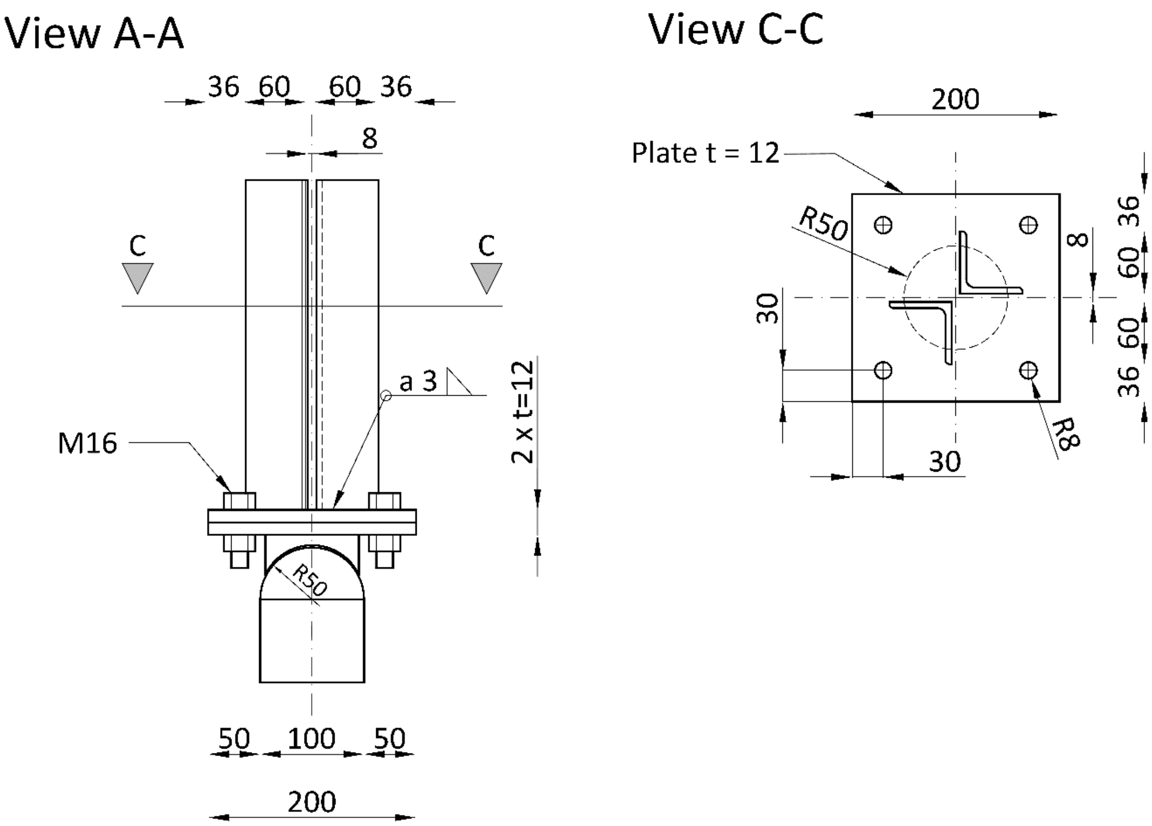


Figure 14: Support conditions for SBE specimen

6.3.2 Packing plate connection

Hereafter, the design of the packing plates for SBE specimens is detailed. As for BBE specimens, four tests are to be performed with fit bolts (no clearance – see Figure 16) and two tests explicitly include the effect of bolt hole clearance (see Figure 17).

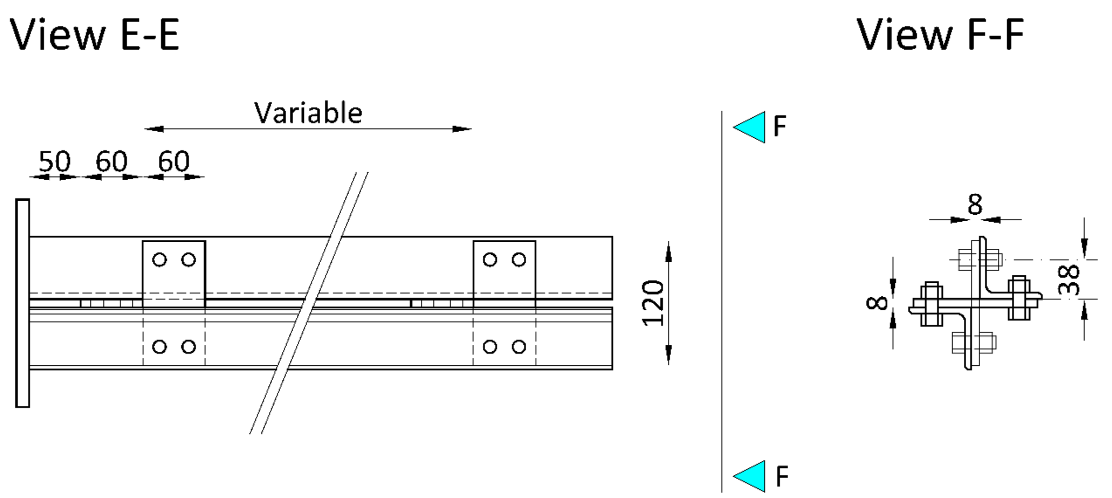


Figure 15: Packing plate connection for SBE specimen

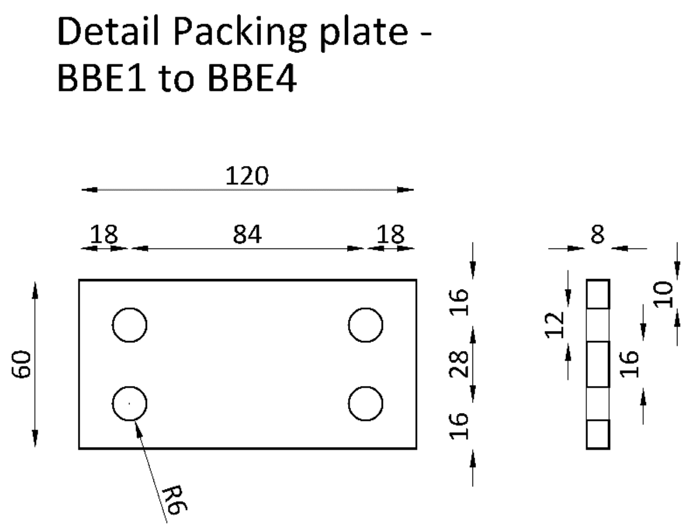


Figure 16: Detail of packing plates without bolt hole clearance – SBE specimen

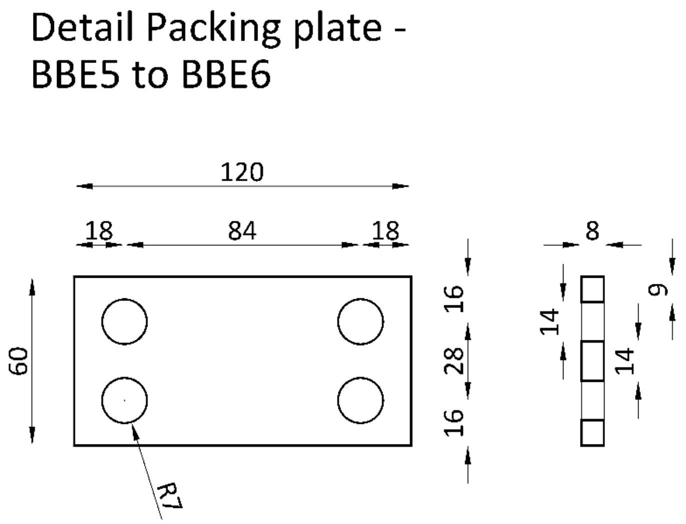


Figure 17: Detail of packing plates with bolt hole clearance – SBE specimen

6.4 SBU specimens

6.4.1 Support conditions

Due to the non-symmetry of SBU members, it is delicate to apply a sole axial force. It appears that slight misalignments may lead to a supplementary first order bending moment. In order to have a better control on this first order bending moment, the axial force is introduced into the gravity centre of the taller angle section. Consequently, the SBU specimens are subject to combined axial force and bending moments. Additional to the advantage, that this design allows a better control on the value of the bending moment, the tested load case corresponds to practical loading conditions for this type of built-up members.
The design of the support conditions is represented in Figure 18. The packing plates are not represented in this figure.

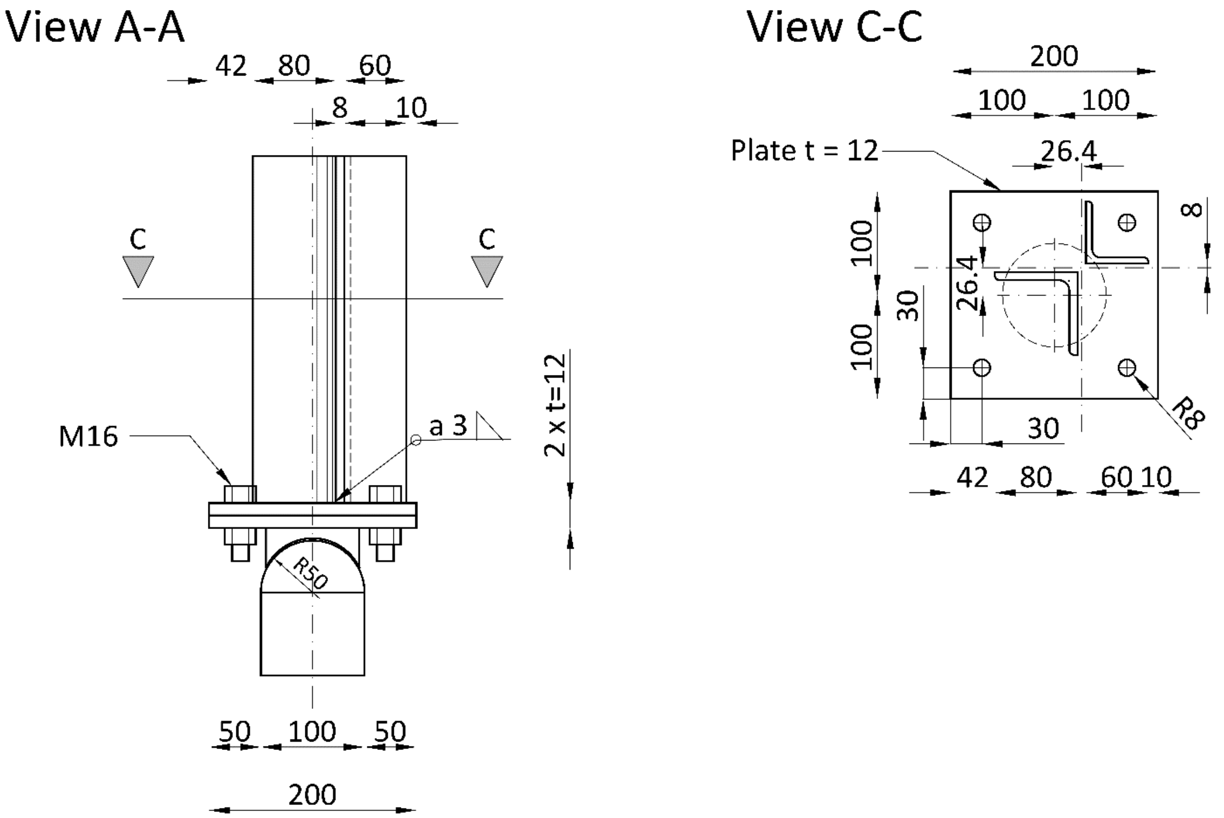


Figure 18: Support conditions for SBU specimen

6.4.2 Packing plate connection

The design of the packing plates for SBU specimens is similar to the packing plates used for SBE specimens. However, for the chosen cross-sections different bolt diameters should be used. Therefore, the diameter of the bolt holes is different, too, as shown in Figure 19 and Figure 20.

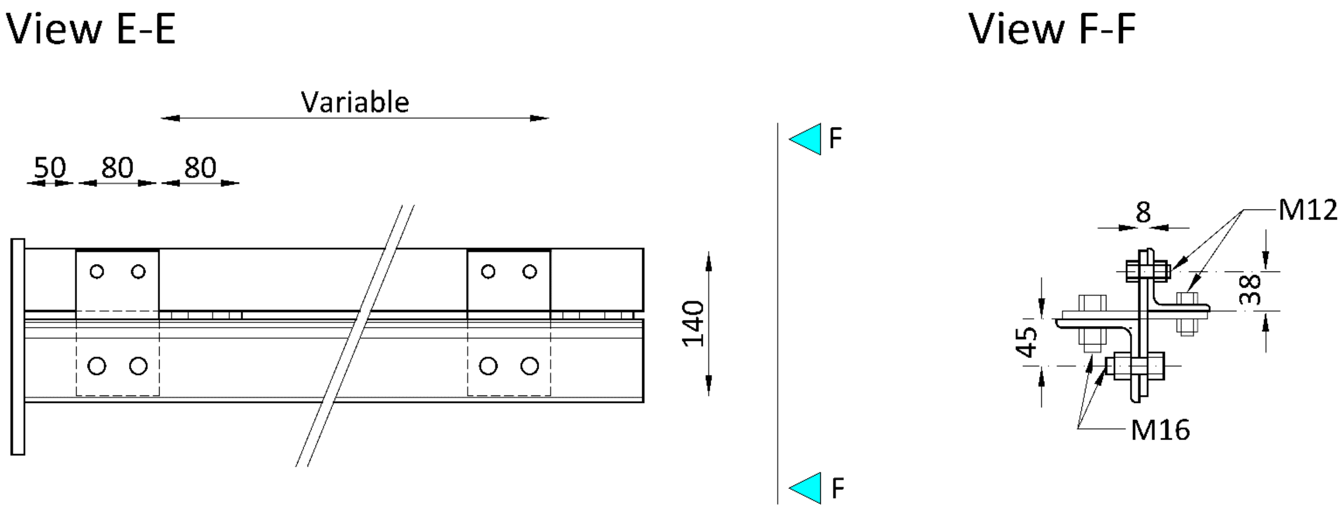


Figure 19: Packing plate connection for SBU specimen

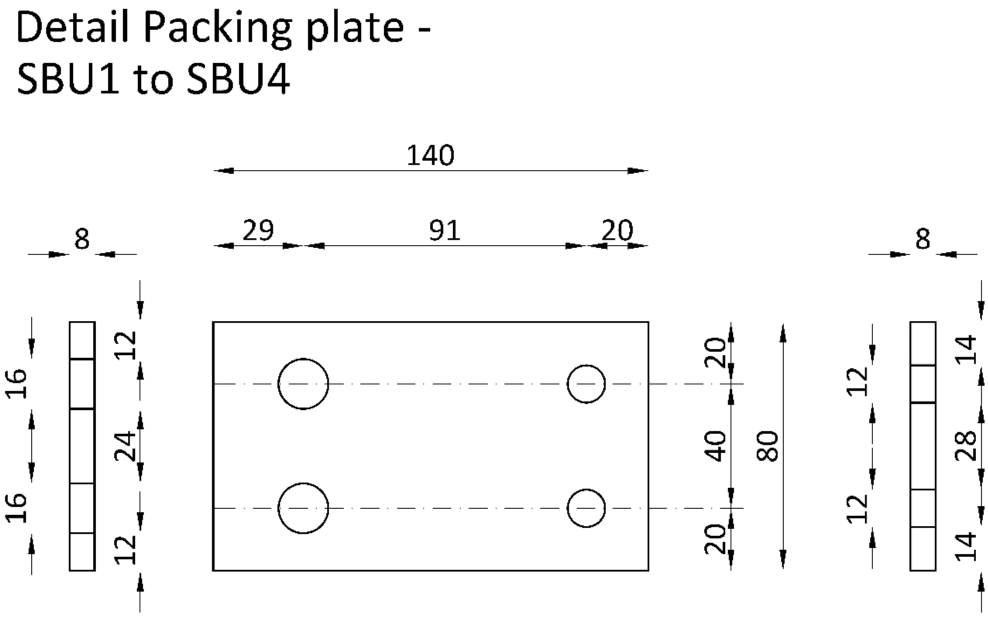


Figure 20: Detail of packing plates for SBU specimen

References

Kitipornchai, S., Lee, H. W. (1986), “Inelastic Experiments on Angle and Tee Struts”, Journal of Constructional Steel Research, Vol. 6, 219-236.

Annexe A – Numerical simulations of the chosen specimens

A.1 Presentation of numerical model

Hereafter, the choice of the test specimens described in paragraph 3.2 is verified through numerical simulations considering relevant imperfection as well as geometric and material non-linearities. These simulations are referred to as GMNIA simulations in the following.

The numerical analysis of the test specimens is performed with ANSYS program. So as to simulate as precisely as possible the behaviour of the laboratory tests, the numerical analysis is based on a solid model with element “Solid 186” of the ANSYS element library. This element possesses 20 nodes (8 nodes on the summit and 12 mid-side nodes) with three degrees of freedom (displacements about the x-, y- and z-axis). “Solid 186” supports plasticity, large deflection and large strain as well as initial state (residual stresses) and is therefore capable to simulate precisely the behaviour of steel sections. A simplification of the numerical model (use of shell elements, simplified modelling of the bolted connections) will be considered for the parametric study. It should be noted that one single bolt per packing plate is used for specimens of type BBE whereas two bolts have to be used per packing plate for specimens of type SBE and SBU as shown in Figure 22.

Figure 21 and Figure 22 show that the angle sections are supposed to be welded onto two endplates. These endplates uniformly distribute the axial force introduced by the actuator. The detailed design of the load introduction for the laboratory tests is presented in paragraph 6.

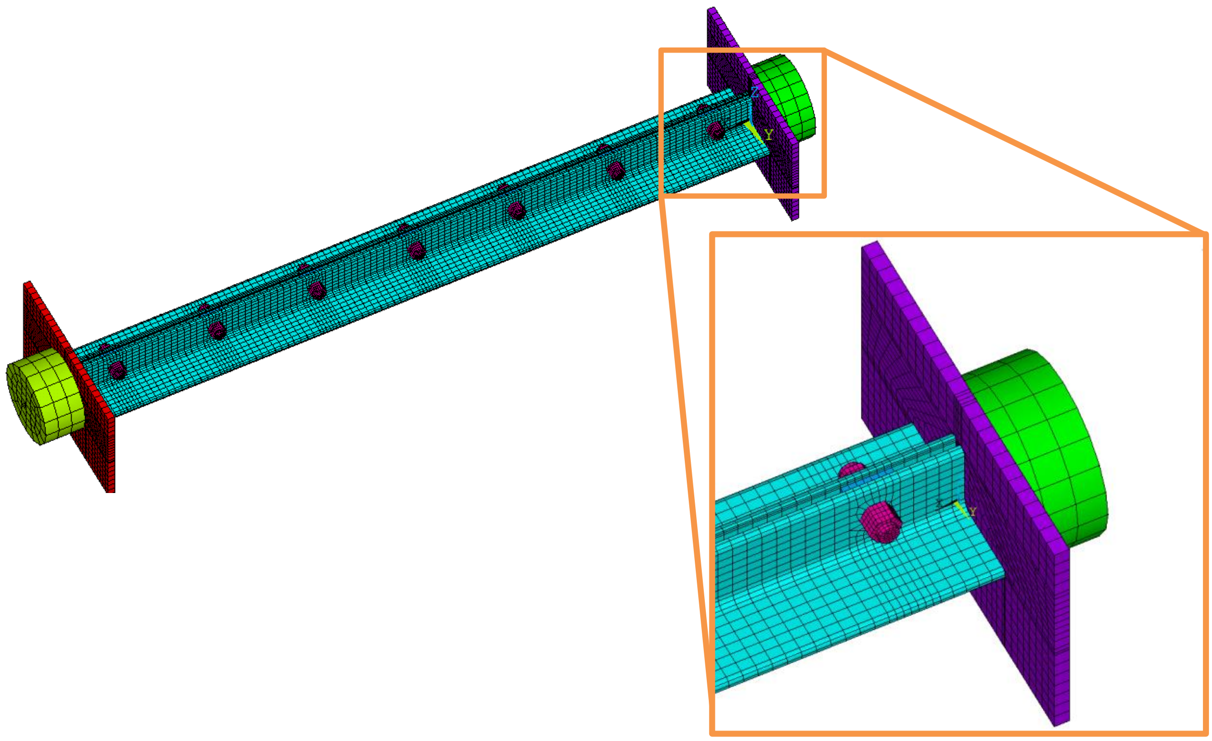


Figure 21: Global view of the numerical model used for the preliminary analysis of the test specimens

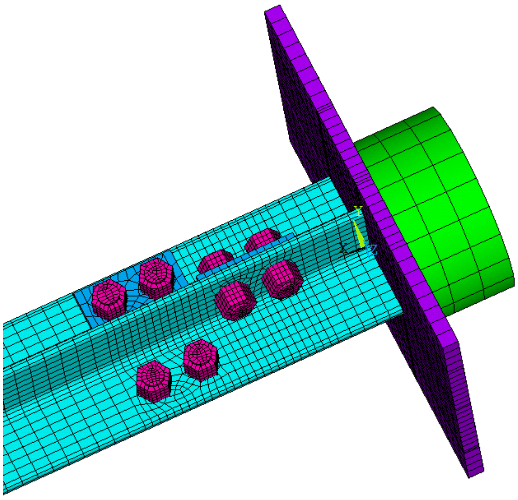


Figure 22 : Detailed view of load introduction for a specimen of type SBE

Figure 23 gives a schematic view of the boundary conditions for the numerical simulations. It should be noted that the same conditions are used independently from the typology of the test specimens (BBE, SBE, SBU). However, an intermediate restraint against vertical displacement is applied at mid-span for specimens BBE in order to insure that member failure is characterized by buckling about the z-z axis as described in paragraph 3.2.1.
Figure 23 also represents that the load is introduced by an imposed axial displacement *u* applied at one member end. At this end, the torsional twist φ is also restrained in the numerical simulations to avoid numeric instability (at least one restraint concerning the rotation about the longitudinal axis is necessary). At the member ends, the boundary conditions are applied at the node situated at the centre of the cylinder represented in green colour in Figure 21 and Figure 23. This node is then linked by the MPC contact technology of ANSYS to the other nodes situated on the outer circular surface of the cylinder. This avoids stress peaks potentially generated by the local application of the boundary conditions.

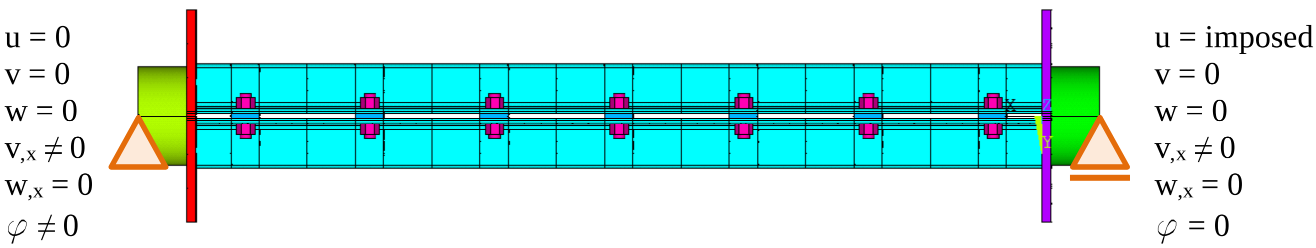


Figure 23: Schematic representation of the boundary conditions for the numerical simulations

In addition to the rigid contact created between the restraint node at the member end and the surface of the cylinder, several contact regions have to be defined so as to represent the real stiffness of the built-up section. These regions are presented in Figure 24 for BBE specimens. Nevertheless, the same principal applies for SBE and SBU specimens.

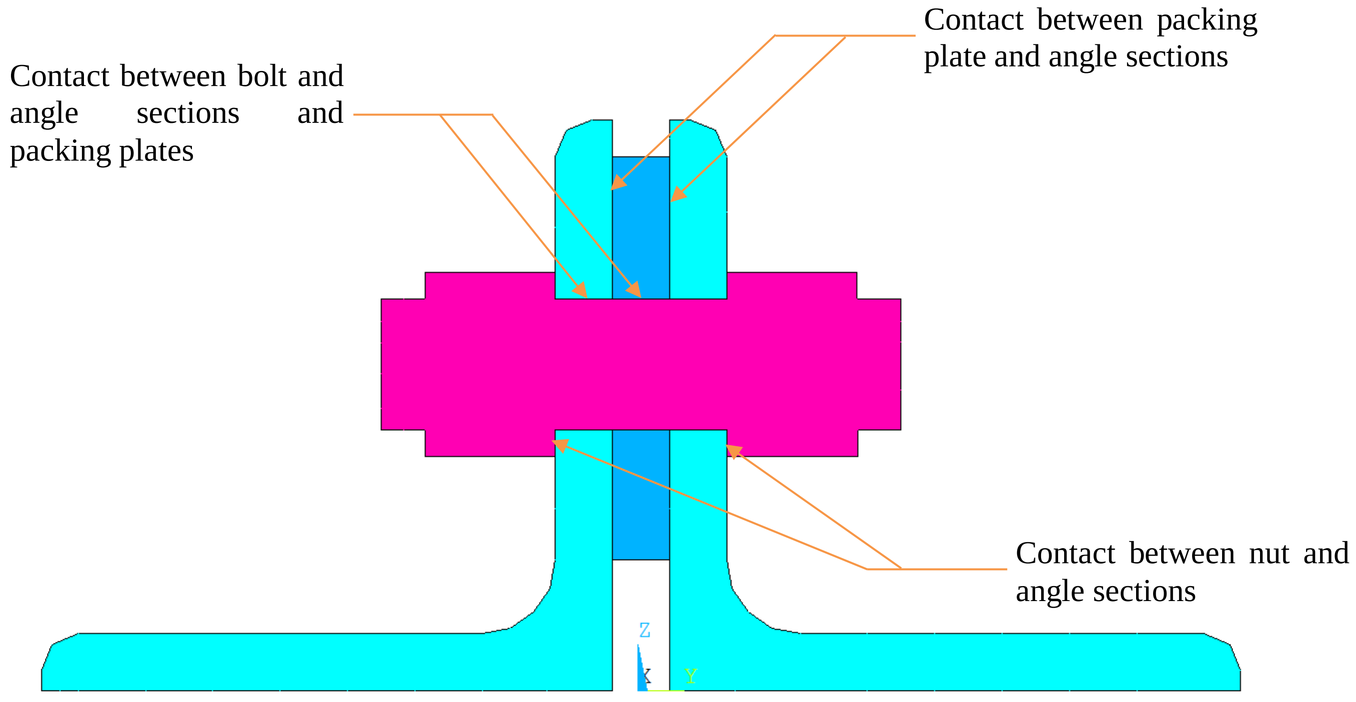


Figure 24: Contact regions for the built-up member

The GMNIA simulations are performed considering an initial geometric imperfection affine to the first (member-) eigenmode with an amplitude of L/1000. For the preliminary simulations of the laboratory tests presented in the next paragraphs a simplified bi-linear material model is used as represented schematically in Figure 25. It should be noted that the laboratory tests will be re-analysed in task 3 of WP 3 based on measured geometric imperfections and the material law obtained with tensile tests. Last, it should be noted that residual stresses are not considered in the following simulations.

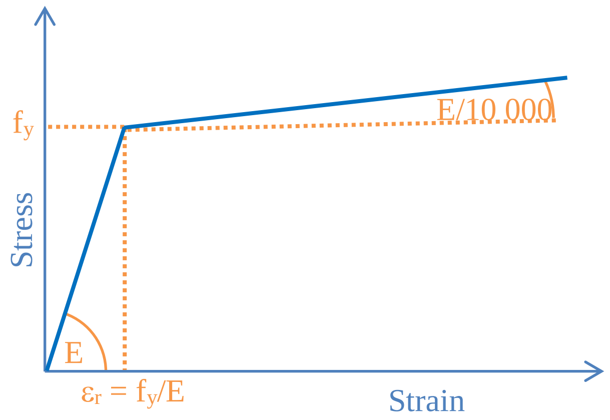


Figure 25: Bi-linear stress-strain curved used for preliminary study of the laboratory tests

A.2 Results of preliminary numerical simulations on BBE specimens

Hereafter, the results obtained for the simulations on BBE specimens are presented. It is to be noted that the preliminary simulations performed to confirm to choice of the test specimens

only concern members without bolt hole clearance in the connection between the angle sections. A more detailed analysis of these tests is performed in task 3 of WP 3 when the results of the laboratory tests are available.
Table 8 summarises the results of the preliminary numerical study. The axial force obtained at the peak load level is compared to the:

- Plastic axial force of the built-up member N_{pl};
- Critical axial force N_{cr} obtained by linear buckling analysis performed on the numerical model;
- Axial force N_b corresponding to the buckling strength of the built-up member determined based on N_{pl} and N_{cr} and calculated with buckling curve b considering that no additional reduction due to the shear flexibility of the connections had to be accounted for (in addition to the influence concerning N_{cr} included in the LBA simulations).

It should be noted that the obtained critical axial force corresponds in all cases to flexural buckling about the major-axis. Also, it is interesting to note that the critical axial force is not identical for tests BBE2 and BBE4 even if their member lengths is identical due to the influence of the packing plates (17 in case of BBE2 and 4 in case of BBE4).

Table 8: Results obtained for tests BBE

Test	Axial force at ultimate limit state N_{ult} (kN)	Plastic axial force of the built-up member N_{pl} (kN)	Critical axial force N_{cr}	Simplified buckling strength N_b
BBE1	629,8	667,4	1927,5	562,5
BBE2	229,2		268,4	210,5
BBE3	488,9		741,5	420,4
BBE4	220,9		257,6	203,5

The following four figures represent the numerically obtained load displacement curves for the studied tests. In additions these figures represent the axial force corresponding to the buckling strength N_b.

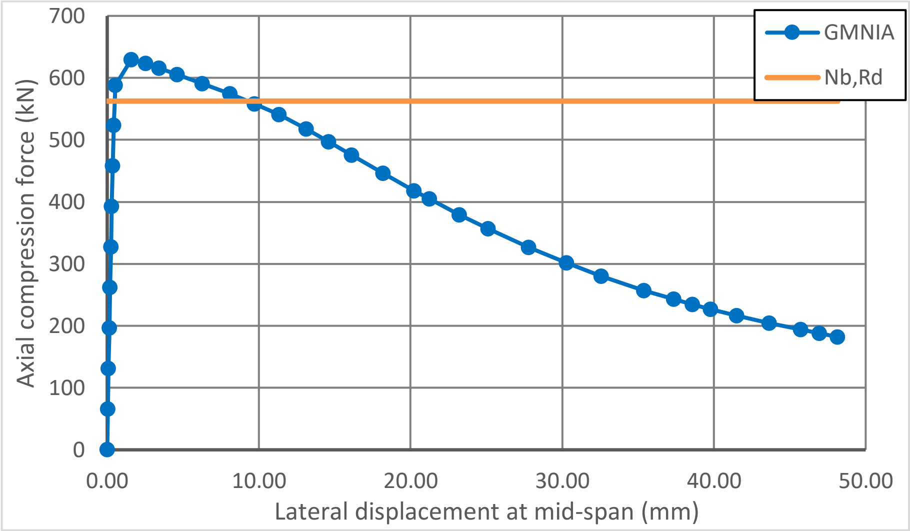


Figure 26: Load-displacement curve for test BBE1

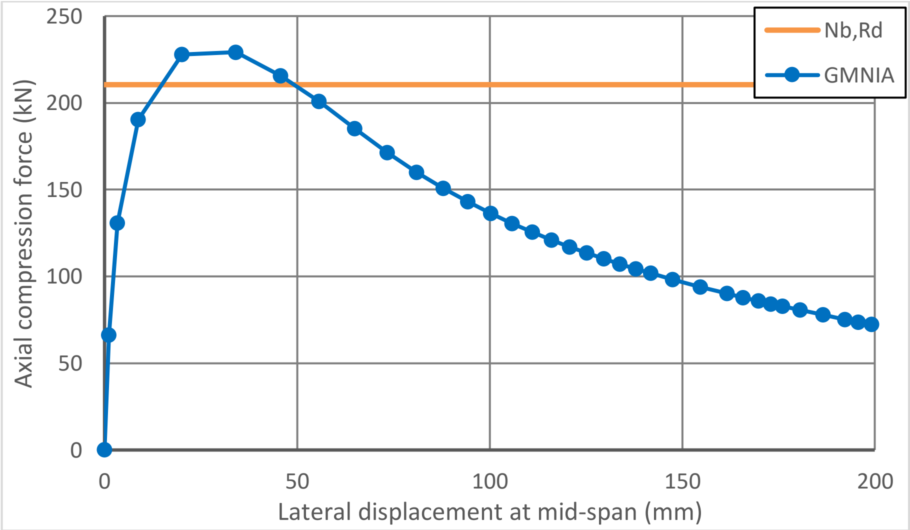


Figure 27: Load-displacement curve for test BBE2

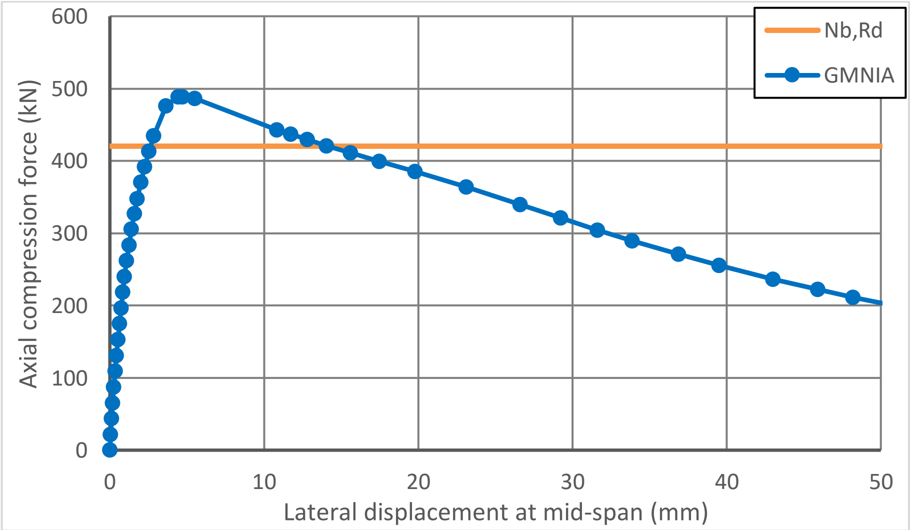


Figure 28: Load-displacement curve for test BBE3

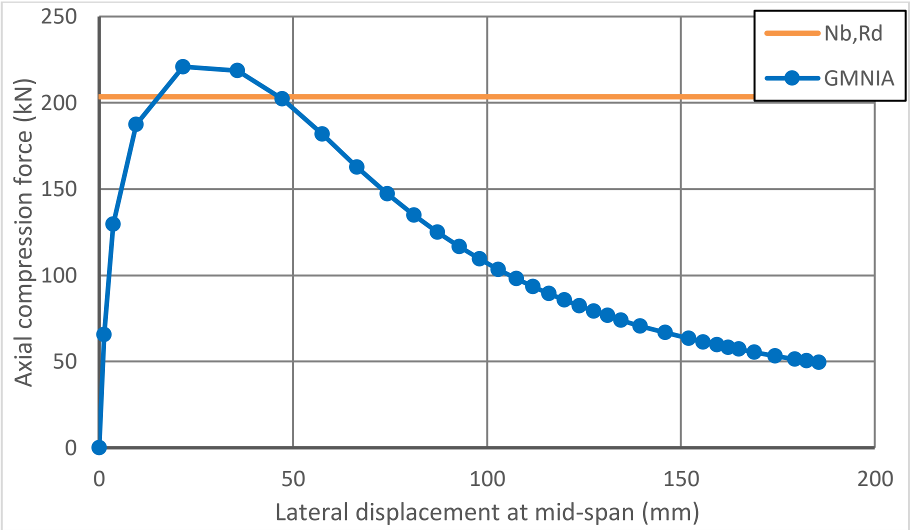


Figure 29: Load-displacement curve for test BBE4

Figure 26 to Figure 29 indicate that the failure of the members is attained for mid-span displacements along the y-y axis (see Figure 2) between 1,5 mm and 35 mm. In order to insure that the failure is attained in the laboratory tests, the equipment should be designed in order to attain at least a **mid-span y-axis displacement of about 100 mm**.
The maximum rotation at peak load level is obtained for test BBE2 as shown in Figure 30 representing the von Mises stress distribution as well as the deformed shape. At this stage the rotation at the supports attains approximatively 0,03 rad. At the load level corresponding to a mid-span y-axis displacement of 100 mm, the rotation at the supports attains approximatively 0,07 rad. Therefore, the equipment in the laboratory should be design to allow a **rotation of at least 0,15 rad**.
As for the rotation at the supports, the imposed axial displacement is highest for test BBE2. However, it attains only of about 3 mm at peak load level and approximatively 8 mm at the load level corresponding to the mid-span y-axis displacement of 100 mm.

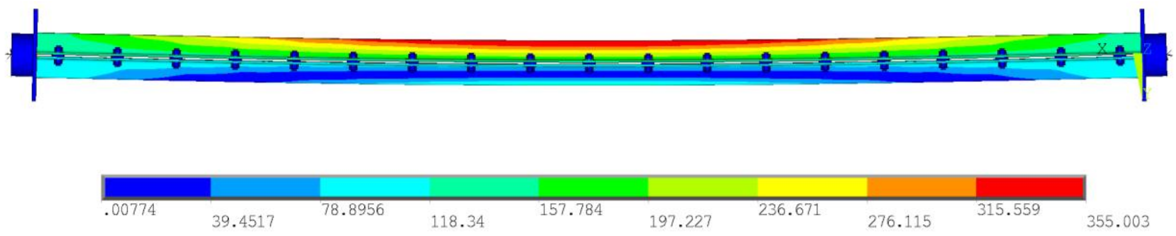


Figure 30: Von Mises stress distribution at peak load level for test BBE2

A.3 Results of preliminary numerical simulations on SBE specimens

Hereafter, the results obtained for the simulations on SBE specimens are presented. As before, the simulations performed to confirm to choice of the test specimens only concern members without bolt hole clearance in the connection between the angle sections.

Table 8 summarises the results of the preliminary numerical study. The axial force obtained at the peak load level is compared to the:

- Plastic axial force of the built-up member N_{pl};
- Critical axial force N_{cr} obtained by linear buckling analysis performed on the numerical model;
- Axial force N_b corresponding to the buckling strength of the built-up member determined based on N_{pl} and N_{cr} and calculated with buckling curve b considering that no additional reduction due to the shear flexibility of the connections had to be accounted for (in addition to the influence concerning N_{cr} included in the LBA simulations).

It should be noted that the obtained critical axial force corresponds in all cases to flexural buckling about the minor-axis of the **built-up member** (and not the one of the individual angle section).

Table 9: Results obtained for tests SBE

Test	Axial force at ultimate limit state N_{ult} (kN)	Plastic axial force of the built-up member N_{pl} (kN)	Critical axial force N_{cr}	Simplified buckling strength N_b
SBE1	223,0	490,6	268,8	197,8
SBE2	133,7		150,6	123,1
SBE3	133,5		150,0	122,7
SBE4	79,8		86,8	75,2

The following four figures represent the numerically obtained load displacement curves for the studied tests. In additions these figures represent the axial force corresponding to the buckling strength N_b.

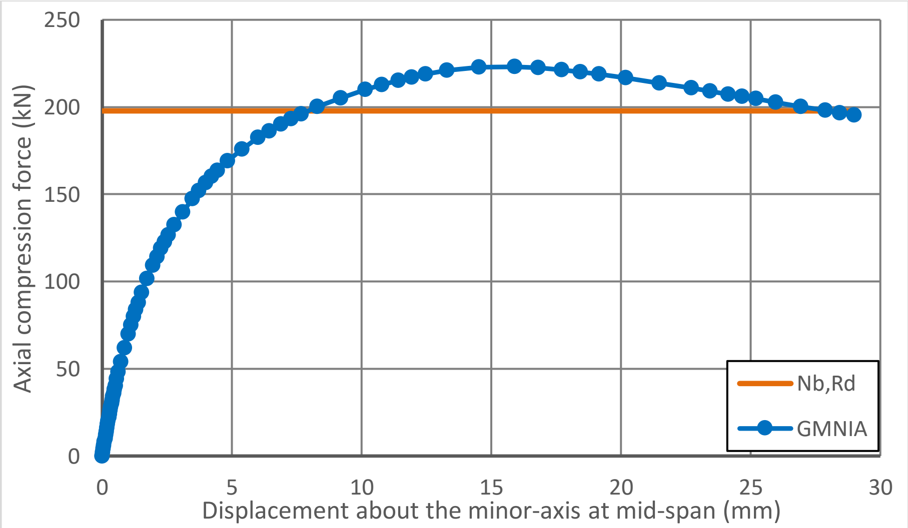


Figure 31: Load-displacement curve for test SBE1

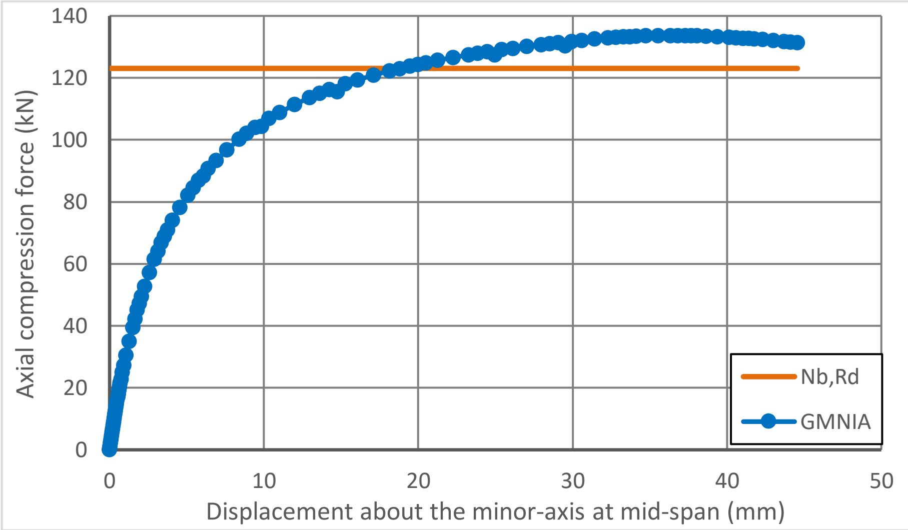


Figure 32: Load-displacement curve for test SBE2

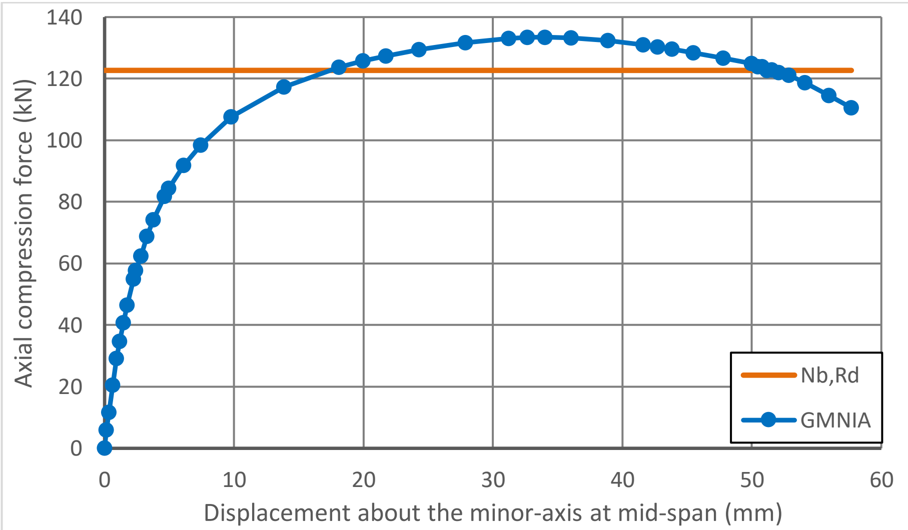


Figure 33: Load-displacement curve for test SBE3

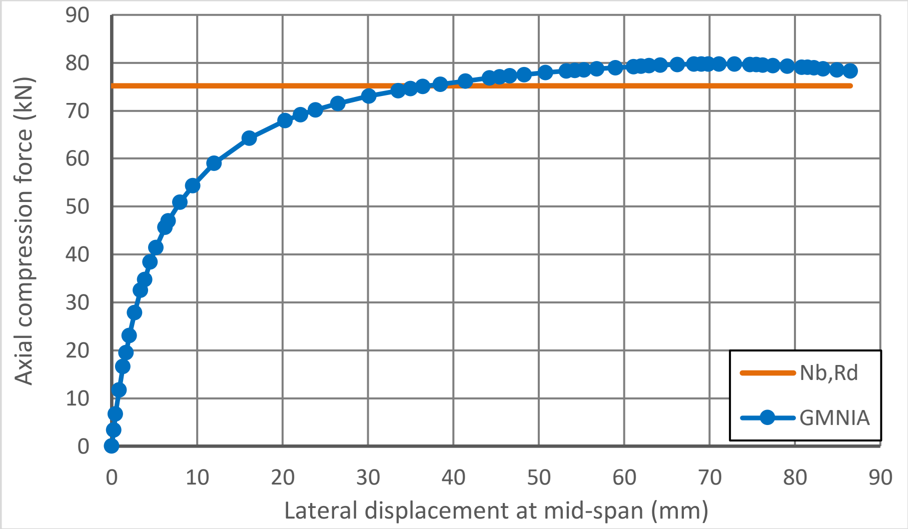


Figure 34: Load-displacement curve for test SBE4

A.4 Results of preliminary numerical simulations on SBU specimens

Hereafter, the results obtained for the simulations on SBU specimens are presented. Table 10 summarises the results of the preliminary numerical study. The axial force obtained at the peak load level is compared to the:

- Plastic axial force of the built-up member N_{pl};
- Critical axial force N_{cr} obtained by linear buckling analysis performed on the numerical model.

It should be noted that the obtained critical axial force corresponds in all cases to flexural buckling about the minor-axis of the **built-up member** (and not the one of the individual angle section).

Table 10: Results obtained for tests SBU

Test	Axial force at ultimate limit state N_{ult} (kN)	Plastic axial force of the built-up member N_{pl} (kN)	Critical axial force N_{cr}
SBE1	223,0	490,6	268,8
SBE2	133,7		150,6
SBE3	133,5		150,0
SBE4	79,8		86,8

The following four figures represent the numerically obtained load displacement curves for the studied tests.

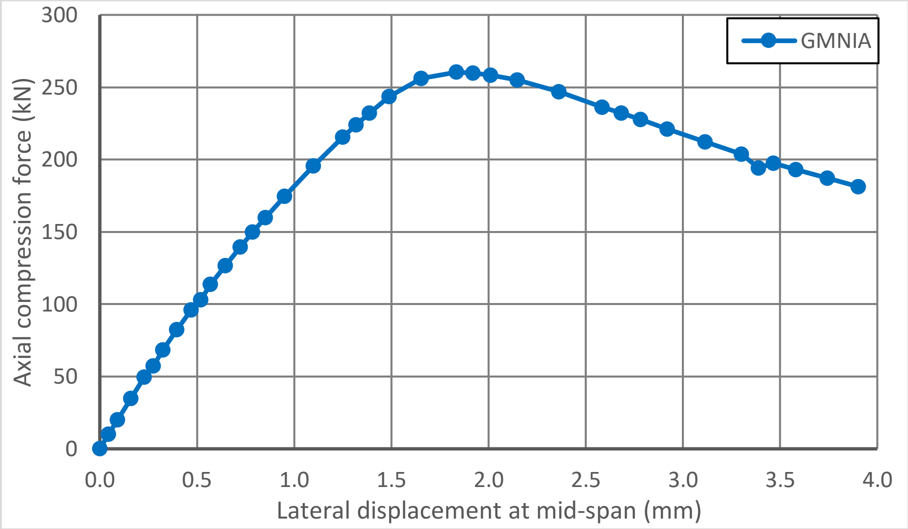


Figure 35: Load-displacement curve for test SBU1

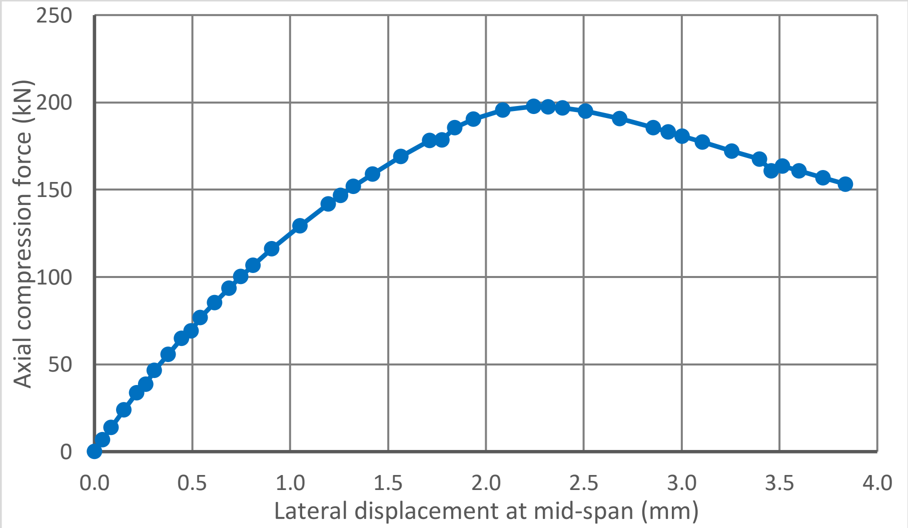


Figure 36: Load-displacement curve for test SBU2

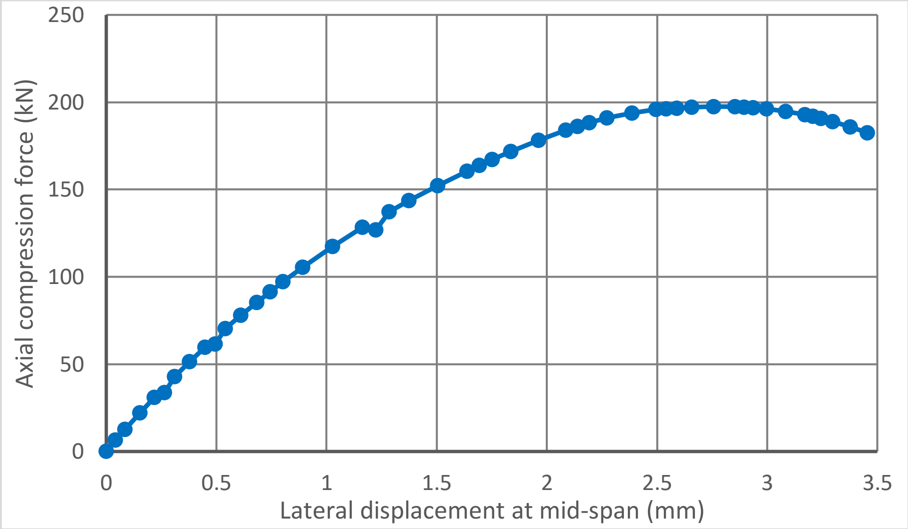


Figure 37: Load-displacement curve for test SBU3

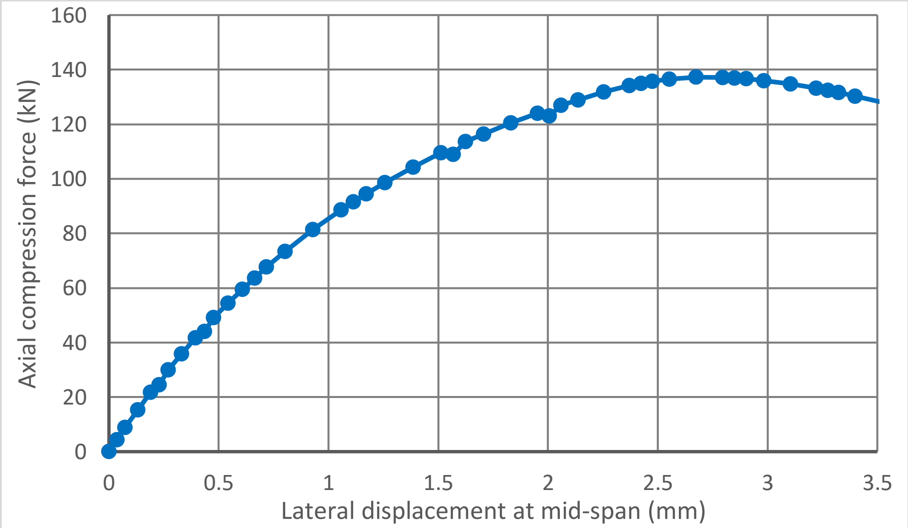


Figure 38: Load-displacement curve for test SBU4