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RESEARCH REPORT NO.I

Experimental testing of prototype with non-adherent layer and processing the obtained data - Experimental Qualification Procedure for Buckling Restrained Braces

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1. IMPLEMENTATION BUCKLING RESTRAINED BARS IN ROMANIA

In Romania, the use of bracing with restrained buckling is regulated in P100-1 / 2013 - Chapter 6: “Frames with bracing with restrained buckling. In these structures the horizontal forces are taken over mainly by elements required for axial stresses. The dissipative areas are located in bracings, whose special composition prevents buckling of the steel core, ensuring a stable and quasi-symmetrical cyclic response of the centrally classic bracing frames.”

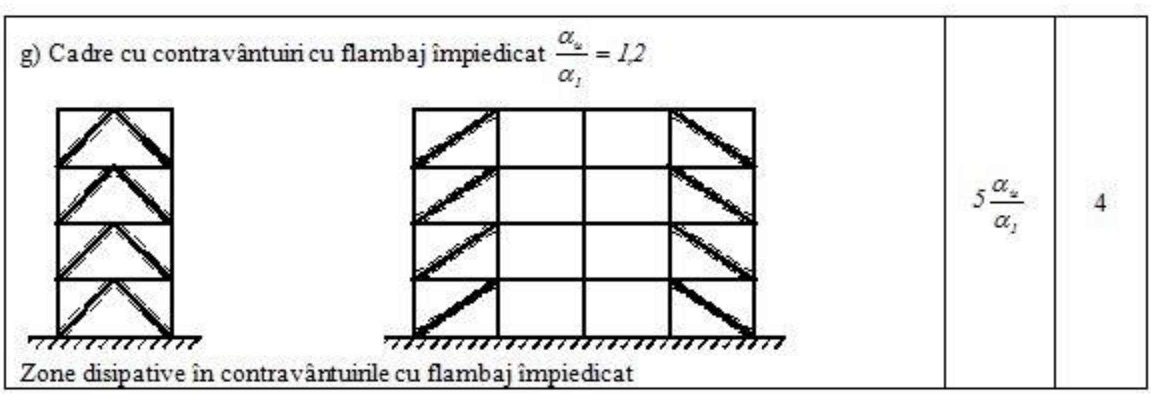

Fig. 1.1 - Behavior factor for frames with BRB

Legend: Cadre cu contravantuiri cu flambaj impiedicat = frames with (wind) bracing with restrained buckling
Zone disipative in contravanturile cu flambaj impiedicat = dissipative areas in (wind) bracing with restrained buckling

Also, in the norm P100-1 / 2013, the following design criteria are presented for the dissipative bars with restrained buckling:

- BRB bracing frames must be designed so that they enter flow before the formation of plastic joints or before the loss of general stability in beams and columns.
- the steel core is inserted in a system that prevents buckling and it must be calculated so as to withstand the axial forces of bracing.
- dissipative bar bracing with restrained buckling must be designed, executed and tested experimentally

The bracing grips and adjacent elements shall be calculated using the corrected bracing capacity. The corrected capacities are determined by experimental tests.

Corrected resistances

- on stretching: $\omega \cdot \gamma_{ov} \cdot f_y \cdot A = \omega \cdot \gamma_{ov} \cdot N_{pl.Rd}$
- on compression: : $\beta \cdot \omega \cdot \gamma_{ov} \cdot f_y \cdot A = \beta \cdot \omega \cdot \gamma_{ov} \cdot N_{pl.Rd}$

where:
$\omega =$ correction factor due to consolidation (obtained experimentally)
$\beta =$ compression capacity correction factor (obtained experimentally)

- $\omega = \frac{T_{max}}{A \cdot f_y}$ (ratio between the maximum tensile force and the flow force in the dissipative bar)
- $\beta = \frac{P_{max}}{T_{max}}$ (ratio between the maximum compressive force and the maximum tensile force in the dissipative bar)

P_{max} ,T_{max} are obtained experimentally on the specimens tested for a deformation value equal to twice the relative drift of the calculation level

$$N_{pl,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} \tag{1.1}$$

where:
A = the cross-sectional area of the steel core
f_y=steel yield strength
γ_{M0}= partial safety factor

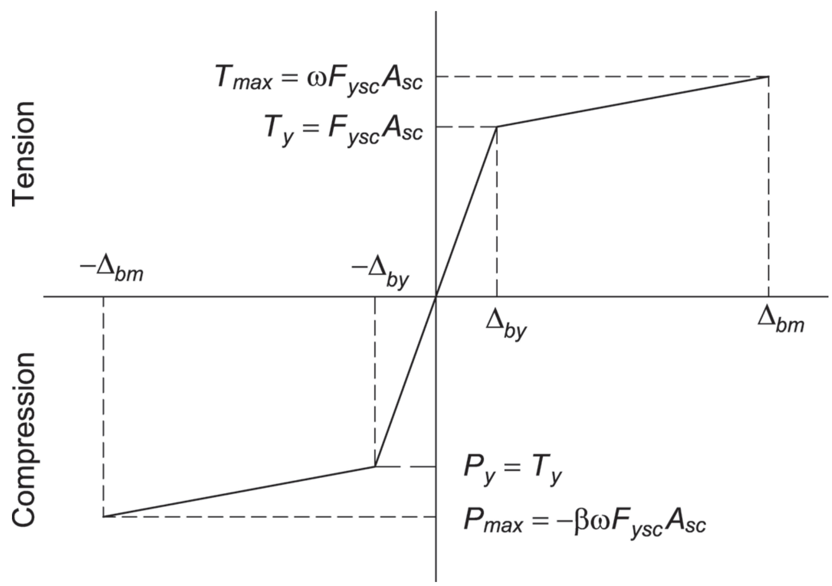

Fig. 1.2 - Behavior of dissipative bars described by the bilinear curve

Pillars and beams will be calculated in the elastic field considering the most unfavorable combination of stresses:

$$N_{Ed} = N_{Ed,G} + \beta \cdot \omega \cdot \gamma_{ov} \cdot \omega^N \cdot N_{Ed,E} \tag{1.2}$$

where:

- $N_{Ed,G}$ = axial design stress from non-seismic actions contained in the group including the seismic action
- $N_{Ed,E}$ = axial design stress in the load grouping that includes the seismic action
- $\omega^N = \frac{N_{pl,Rd}}{N_{Ed}}$ calculated for each direction of the structure and to also meet the condition: $\beta \cdot \omega \cdot \gamma_{ov} \cdot \omega^N < q$ (q= the behavior factor of the structure).

The ability to join bracings with structural elements must be :

$$R_d \geq 1{,}1 \cdot \beta \cdot \omega \cdot \gamma_{ov} \cdot N_{pl.Rd} \tag{1.3}$$

In the European standard EN15129: 2009 "Common types of anti-seismic devices", dissipative bars with restrained buckling are classified as Displacement Dependents Devices (DDDs) and the performance requirements, test methods, materials from which they are made and the quality control process in the factory are presented.

Eurocode 3 (SR EN 1993-1-1) contains the calculation relationships for strength and stability checks. Eurocode 8 (SR EN 1998-1-1) does not present simplified design methods for dissipative bars with restrained buckling.

2. DESCRIPTION OF ANALYZED STRUCTURES

2.1 Description of the Structures

This paper analyzes the structural models that aim to highlight certain characteristics favorable or unfavorable to bracing with BRB used in multi-storey metal structures. The considered structures are configured with inverted V-shaped center bracings with dissipating bars with restrained buckling. The basic building is a multi-storey office building, located in Bucharest, provided with a braced central core and centrally braced perimeter frames (fig.2.1).

The analyzed structure is composed of 6 openings of 8.10m and 5 beams of 8.10m. The level height is 3.50m, the structures considered having between 5 (GF + 4) and 15 levels (GF + 14). The steel used is S355 (cf. [12] SR EN 10025-2 / 2004).

For the dimensioning of the structural elements, the verification relationships from [5] Eurocode 3, Design of steel structures - Part 1-1: General rules and regulations for buildings were used. The sizing of the bracing systems was made with the observance of the same value of the design seismic load and in compliance with the provisions contained in the Romanian seismic design code: [4] P100-1 / 2013, Seismic design code - Part 1: Design provisions for buildings but also the provisions contained in [6] Eurocode 8, Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings.

For each model, the aim was to create a favorable global plastic mechanism for dissipating the energy induced in the structure by the earthquake.

The pillars used for the analyzed structures had cross sections of the “Maltese cross” type and the main and secondary beams of the “I (double - T)” type. The diagonals were provided with BRB, with rectangular cross sections.

Figure 2.1 shows the plan compliance of the studied calculation models:

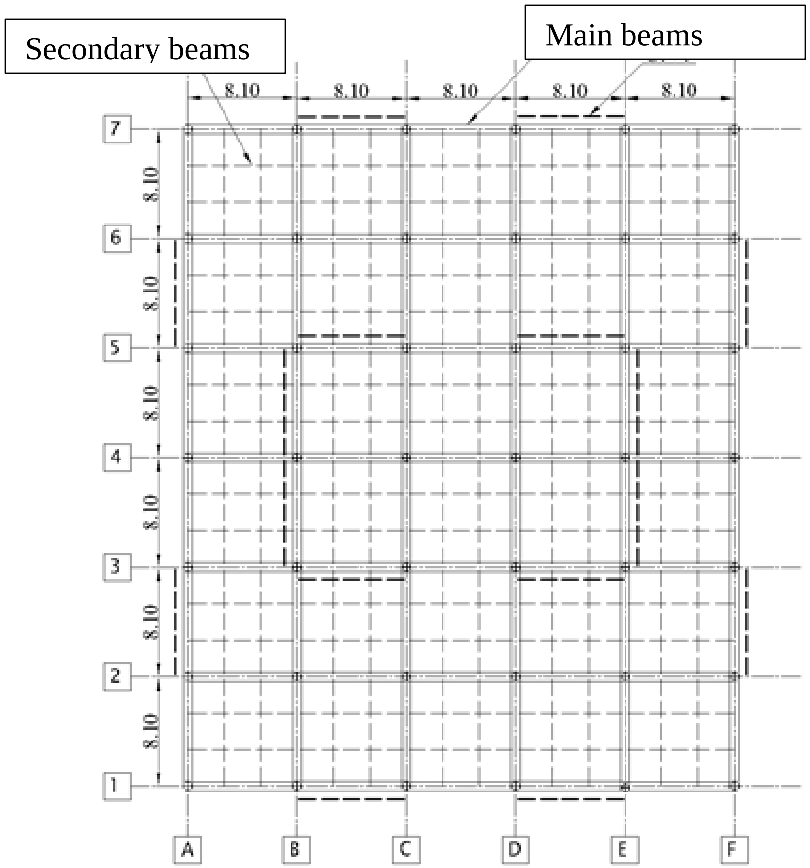

Fig. 2.1 – The plan of the considered structures

For the design of bracings with restrained buckling, the design rules for capacity were followed. The dissipative bars assigned for each bracing are approximately equal to the ratio between the required compressive force and 0.9 • f_y, so the sections can be easily modified in order to meet the conditions of strength and drift.

The design process for dissipative bars with restrained buckling in high ductility systems is as follows:

- calculation of the basic shear force of the structure, taking into account an average behavior factor q = 4 (DCM - conf. P100-1 / 2013) or high q = 6-7 (DCH)
- - structural analysis: determination of the strength and rigidity necessary for the elements
- design of non-dissipative elements: beams, pillars
- for the verification of the structure, non-linear static analysis (pushover analysis) is performed and the verifications are performed according to the design based on the capacity spectra:

verification of the capacity of the elements for the target displacement level and of the maximum deformations for bracing.
- obtaining the necessary resistance and rigidity of braces with restrained buckling .
- equipping the structure with braces with restrained buckling
- redesigning the non-dissipative elements from the chosen structures
- resumption of the nonlinear analysis (pushover) for the final verification of the structure based on the capacity spectra.

Beams, pillars and bracings with restrained buckling have been designed at the maximum load level that can occur during the code earthquake, also taking into account the resistance factor..

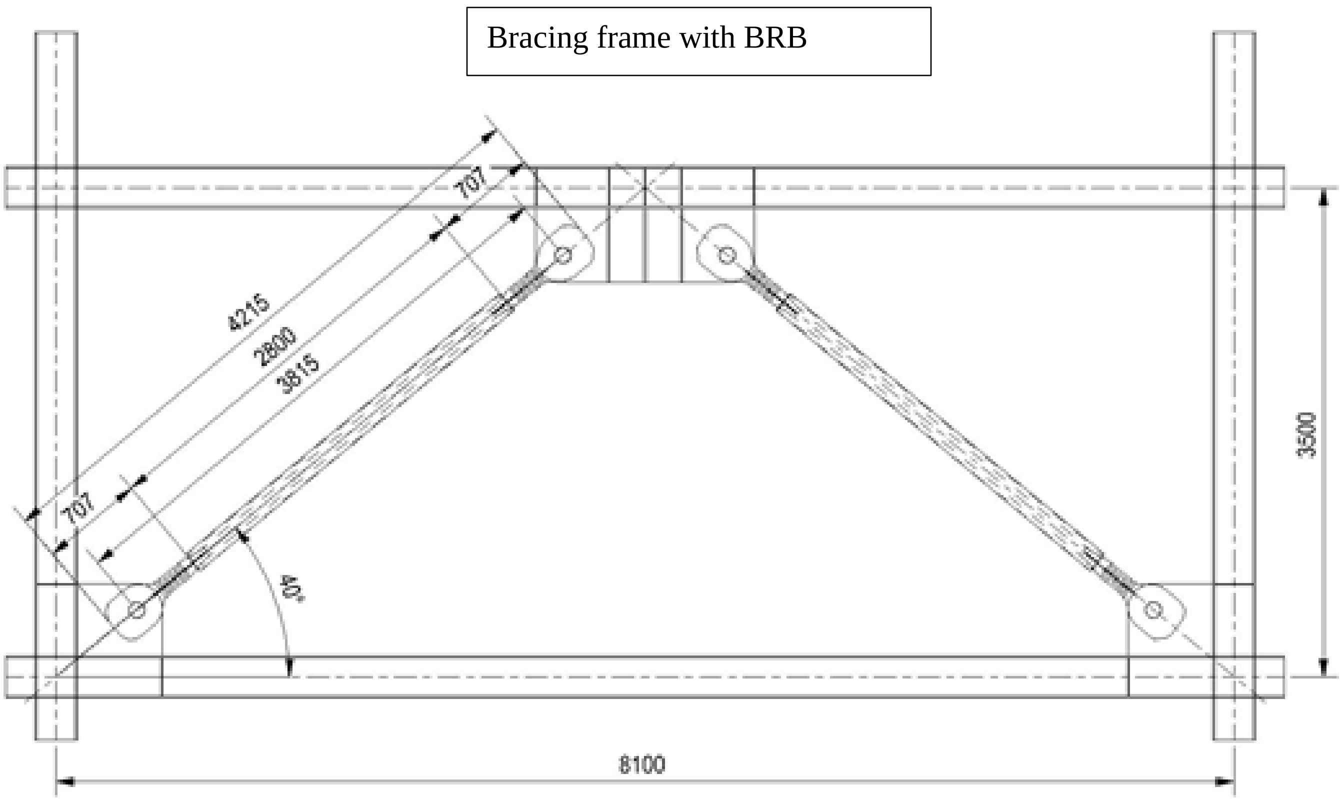

Fig. 2.2 – The braced frame with BRB from the considered calculation models

2.2 Verification of Lateral Drifts

The main purpose of the drift verification is to ensure a minimum level of rigidity of the structure. By limiting lateral drifts, the aim is to maintain degradation at an acceptable level.

2.2.1 Verification of Lateral Drifts at the Ultimate Limit State

Verification of lateral drifts at the ultimate limit state aims to avoid the loss of human life in the event of a major earthquake by preventing the collapse of non-structural elements.

Drift verification is based on the expression:

$$d_r^{ULS} = c \cdot q \cdot d_{re} \leq d_{r,a}^{ULS} \tag{2.2}$$

where:

- d_r^{ULS} – relative level drift under the ULS-associated seismic action
- $d_{r,a}^{ULS}$ – the allowable value of the relative level drift. The recommended value for the relative allowable level drift is $d_{r,a}^{ULS} = 0{,}025 \cdot h$
- c – drift amplification factor

$$c = \begin{cases} \dfrac{1{,}1 \cdot \gamma_{ov} \cdot \Omega}{q} + \left(1 - \dfrac{1{,}1 \cdot \gamma_{ov} \cdot \Omega}{q}\right) \cdot \dfrac{T_C}{T_1} \geq 3, \;\; if\ T_1 < T_C \\ 1{,}0, \;\; if\ T_1 \geq T_C \end{cases} \tag{2.3}$$

The intrinsic periods for the first two vibration modes (translation modes according to the main directions of the structure) are shorter than T_C. Since the behavior factor q and the resistance have equal values, the factor c has the value c = 1,0 for both directions of the structure.

The floor drift d_r^{ULS} at the ultimate limit state for the considered calculation models was limited to the value $d_r^{ULS} = 0{,}02 \cdot h = 0{,}02 \cdot 3500mm = 70mm$.

2.3 Calculation and Sizing of Wind Bracings with Restrained Buckling

In the article "Type testing of buckling restrained braces according to EN 15129" [12] were published the results of tests on dissipative bars with restrained buckling produced by StarSeismic Ltd. The same article presents that the values obtained in the tests performed on the dissipative bars, the correction factor of the tensile capacity is higher than 1.4, different from the minimum value 1.0 .

The correction coefficients were thus determined:

$$\omega = \frac{V_{bd,T}}{f_{ya,c} \cdot A_y} = \frac{V_{bd,T}}{F_{ac,c}} \tag{2.4}$$

where:

- $V_{bd,T}$= the capacity of the dissipative bar with stretch-restrained buckling for the drift at which it was designed
- $f_{ya,c}$ = the yield resistance of the steel core, measured during the test
- A_y= the cross-sectional area of the steel core
- $F_{ac,c}$ = the real yield resistance capacity of the dissipative bar with restrained buckling

$$\beta = \frac{V_{bd,C}}{V_{bd,T}} \tag{2.5}$$

where:

- $V_{bd,C}$= the capacity of the dissipative bar with compression-restrained buckling for the drift at which it was designed

$$\beta_{average,tests} = 1.365 \text{ [12]}$$
$$\omega_{average,tests} = 1.434 \text{ [12]}$$

The European standard EN15129 requires the determination of a theoretical bilinear curve in order to characterize the behavior of dissipative bars. The bilinear curve is represented in figure 2.3, taking into account the correction factors obtained from the tests:

- correction factor for compressive strength capacity : $\beta \cdot \omega = 1.365 \cdot 1.434 = 1.96$
- correction factor for tensile strength capacity $\omega = 1.434$

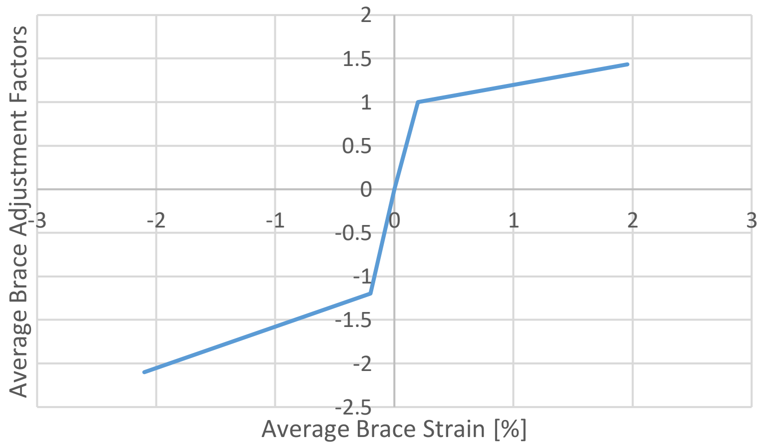

Fig. 2.3 - Behavior of dissipative bars described by the bilinear curve

Example: PL70x15 Section (Section used for the tested BRB Prototype)

Strength capacity of the dissipative bar:

$$A_{core,steel} = 1050\ mm^2$$
$$\gamma_{ov} = 1.30 \text{ (for steel S275)}$$

$$T_y = C_y\ = 1050 \cdot 280 \cdot 10^{-3} = 294\ kN \tag{2.6}$$

$$T_{max} = \gamma_{ov} \cdot \beta \cdot T_y = 1.30\ \cdot 1.365\ \cdot 294 = 521\ kN \tag{2.7}$$

$$C_{max} = \gamma_{ov} \cdot \omega \cdot \beta \cdot T_y = 1.30 \cdot 1.434 \cdot 1.365 \cdot 294 = 748\ kN \qquad (2.8)$$

Deformation capacity of the bar in the elastic range:

$$\varepsilon_{el} = \frac{\sigma}{E} = \frac{280}{2.1 \cdot 10^5} = 0.00131 \qquad (2.9)$$

$$\Delta_{el} = \varepsilon_{el} \cdot L = 0.00131 \cdot 3815 = 5.1\ mm \qquad (2.10)$$

Dissipative bars with restrained buckling were modeled as linear elements. The nonlinear behavior was achieved by defining a plastic joint at half the length of the element as in the following figure:

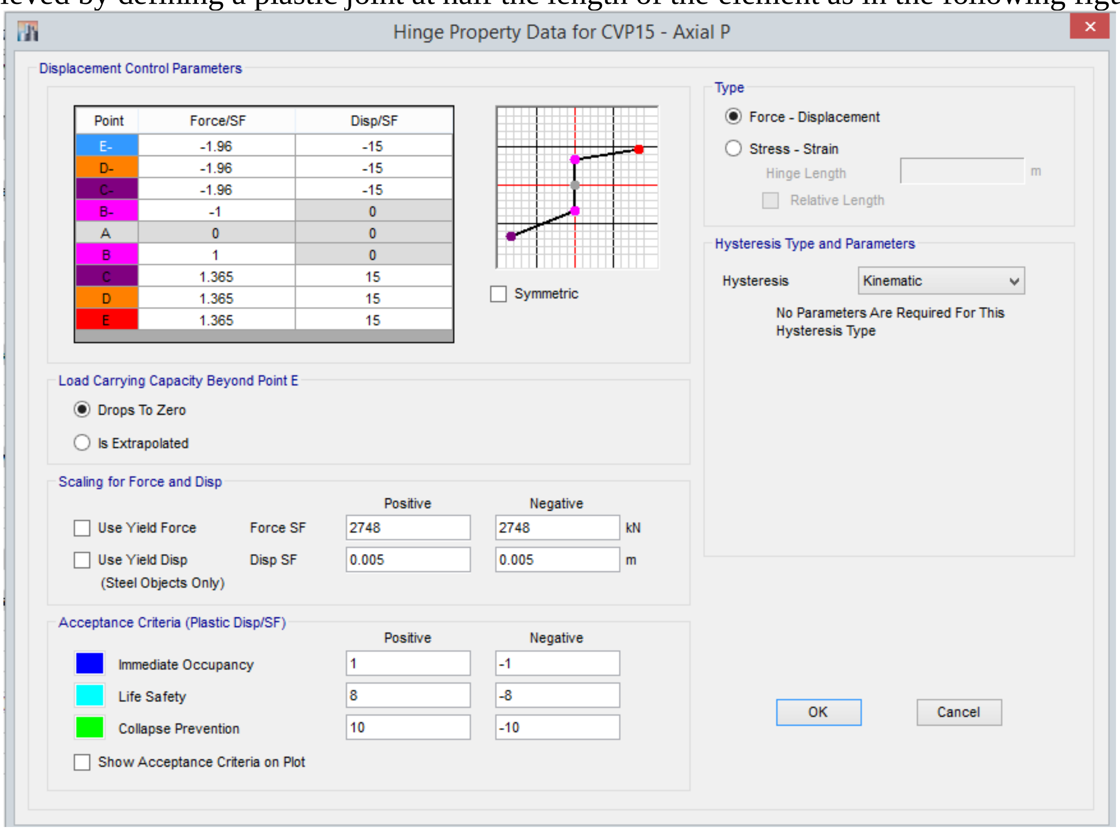

Fig. 2.2 - Defining the plastic joint for dissipative bar in ETABS

The dissipative bars were modeled using linear elements with plastic joints at the ends. Plastic joints are defined with increased compressive strength compared to tensile strength due to the compression factor of the compressive capacity.

Following the linear static calculation, compression and stretching efforts resulted in each diagonal N_{Ed}. The sizing of the BRBs was done following the recommendations in the StarSeismic Design Guide.

The area required for bracings with restrained buckling is obtained with the following formula:

$$A_{nec} = \frac{P}{0.9 \cdot f_y} \tag{2.13}$$

where:

- P = maximum compression / stretching stress from bracing
- f_y = the yield limit of the steel core.

In order to model the hysteretic behavior of the dissipative bars with restrained buckling, the correction factors of the compressive and tensile strength capacity ω = 1,434 and β = 1,365 were preliminarily chosen for the calculation models. With the help of the correction factors, the capacities of resistance to reaching the yield limit were calculated, as follows:

- corrected compressive strength capacity: $\beta \cdot \omega \cdot \gamma_{ov} \cdot N_{pl,Rd}$
- tensile strength capacity $\omega \cdot \gamma_{ov} \cdot N_{pl,Rd}$

$\omega =$ correction factor of the compressive strength represents the ratio between the maximum compressive force P_{max} and maximum tensile force T_{max} (for the experimentally loaded specimen for a deformation corresponding to a value equal to twice the relative drift of the calculation level)

$\omega =$ the correction factor due to hardening and which represents the stress between the maximum tensile force T_{max} and the ability to withstand the yield limit measured in the core of the bracing $f_{y,m}$.

Each dissipative bar with restrained buckling has a total length of 4.15 m of which the plasticization area represents approximately 60%, which represents 2.55 m.

2.4 Design of Frames with Wind Bracing with Restrained Buckling

Frames with restrained buckling bracing are characterized by the ability of braces to work in the plastic field as well in compression as in stretching. In frames equipped with restrained buckling bracings, the braces dissipate energy through stable hysteretic cycles at compression and tension. Figure 2.6 shows the characteristic hysteretic behavior for this type of bracing compared to the behavior of a common bracing. This behavior is obtained by limiting the buckling of the steel core with the help of the buckling restraining system and thus the axial stress is decoupled from the buckling resistance by bending. The axial load is limited to the steel core while the buckling locking system, usually a pipe, resists the overall bending of the bracing and prevents the upper buckling modes of the steel core.

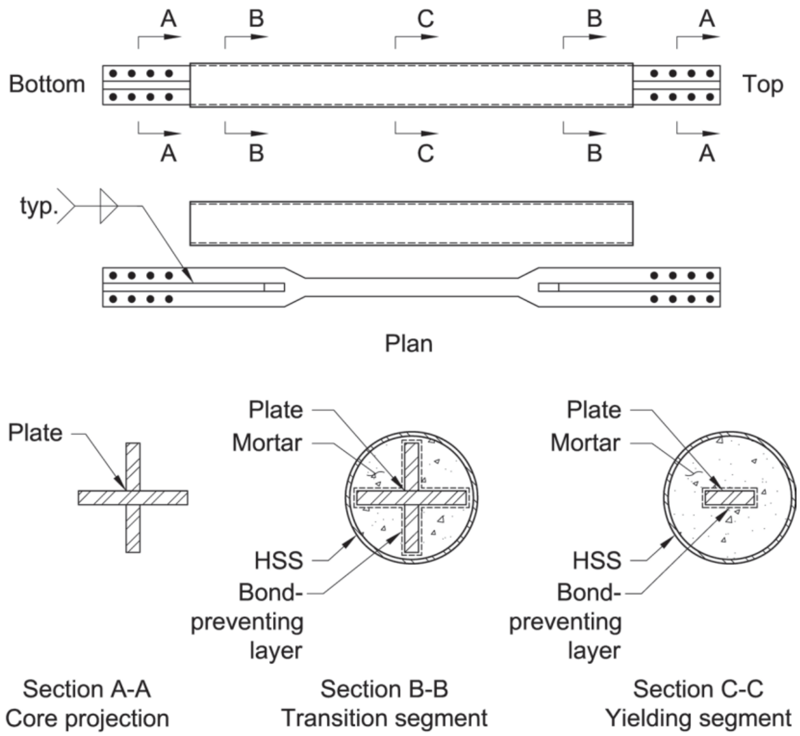

Fig. 2.5 Usual details of bars with restrained buckling [8]

Frames with bracings with restrained buckling are made up of columns, beams and braces, all of which are primarily subjected to axial stresses. Bracings with restrained buckling (BRBs) are composed of a steel core and a buckling restraining system surrounding the steel core. In addition to the scheme shown in Figure 2.5, other examples of BRB can be found in Watanabe et al. “Properties of brace encased in buckling-restraining concrete and steel tube. Proceedings of the 9th World Conference on Earthquake Engineering (1988) ”; Wada et al. “Damage tolerant structure” (1994); and Clark et al. “Design procedures for buildings incorporating hysteretic damping devices (1999). The steel core of the BRB is the primary source of energy dissipation. During an earthquake, the steel core is expected to suffer significant inelastic deformations.

Frames with bracings with restrained buckling can provide elastic rigidity comparable to that of eccentrically braced frames. Large-scale laboratory tests indicate that well-designed and detailed stiffening elements of the frames with bracings with restrained buckling have symmetrical and stable hysteretic behavior when subjected to tensile and compressive loads by significant inelastic deformations. The ductility and energy dissipation capacity of frames with bracings with restrained buckling is expected to be comparable to that of non-braced frames and higher than with centrally braced frames. This high ductility is obtained by limiting the buckling of the steel core.

The provisions mentioned are based on the use of bracings with retrained buckling models qualified by testing. The regulations ensure that bracing is used only within the limits of their proven deformation capacity, and that failure modes, other than the stable entry into the plastic field of the steel core, are restrained at the maximum floor drift corresponding to the design earthquake.

For analyzes performed using linear methods, the maximum inelastic deformations for this system are defined as those corresponding to 200% of the design drift. For hysteretic nonlinear analyzes, the maximum inelastic deformations can be taken directly from the analysis results.

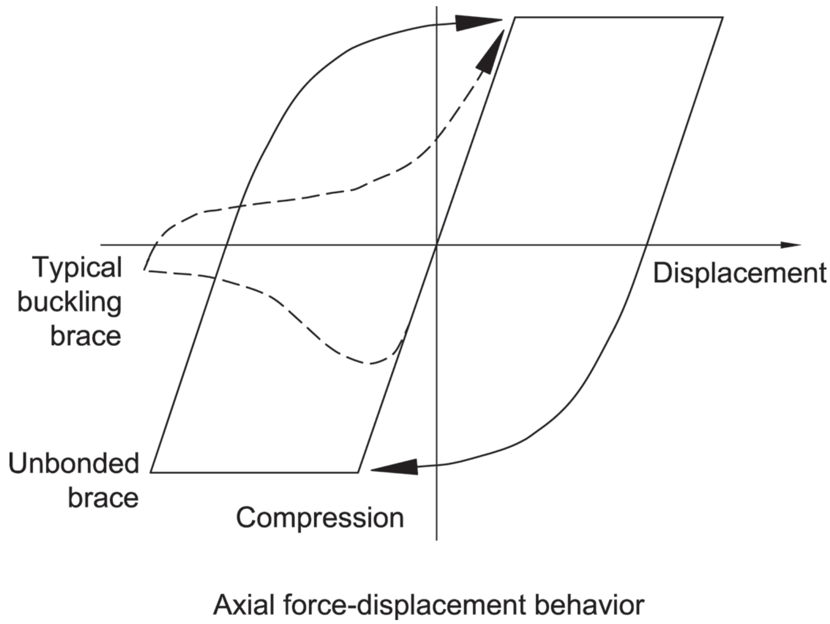

Fig. 2.6. Hysteretic behavior of BRBs [8]

A minimum floor drift of 2% for tests is required to determine the assumed deformation. This approach is consistent with the linear analysis equations for drift design in ASCE / SEI 7 and the FEMA P-750 recommendations. It is also observed that the consequences of the loss of joint stability due to actual seismic displacements exceeding the calculated values can be severe.

Bars with restrained buckling must thus have a higher deformation capacity than that indicated directly by linear static analysis.

The value of 200% of the design drift for the expected deformations of the bracing represents the average of the maximum floor drift, during the seismic movements, having the chance of exceeding 10% in 50 years (Fahnestock et al., 2003; Sabelli et al., 2003). Exceeding the maximum value of BRB deformation can lead to poor behavior, such as buckling, but this does not equate to failure. Detailing and testing at higher deformations of BRBs will ensure greater reliability and better performance.

The design engineer using these recommendations is strongly encouraged to consider the effects of bracing configuration and proportion on the formation of potential building plasticization mechanisms. The axial yield resistance of the core, Pysc, can be determined precisely with the final cross-sectional area of the core determined by dividing the bracing capacity by the effective strength of the material established by testing the specimens, multiplied by a strength factor. In some cases, the cross-sectional area will be regulated by bracing rigidity requirements to limit drift. In both cases, a careful adjustment of the bracing can make the distribution of the laminate on the height of the building much more likely than in ordinary frames.

It is also recommended that engineers consult the following documents to better understand how these devices work: Uang and Nakashima (2003); Watanabe et al. (1988); Reina and Normile (1997); Clark et al. (1999); Tremblay et al. (1999); and Kalyanaraman et al. (1998).

The design provisions for frames with braces with restrained buckling are based on a reliable and trustworthy performance of braces with restrained buckling. To ensure this performance, a quality assurance plan is required. These measures are in addition to those contained in the Standard Code of Practice (AISC, 2016). Examples of measures that can be provided for quality assurance are:

- Special inspection of the manufacture of braces. The inspection may include confirmation of manufacturing and centering tolerances, as well as non-destructive testing (NDT) methods for the evaluation of the final product.
- Participation of the BRB manufacturer in a recognized quality certification program. The certification must include documentation demonstrating that the manufacturer's quality assurance plan is in accordance with the requirements, provisions and regulations in force. Production and quality control procedures should be equivalent to or better than those used in the manufacture of test specimens.

3. EXPERIMENTAL QUALIFICATION PROCEDURE FOR WIND BRACINGS WITH RESTRAINED BUCKLING

The experimental qualification procedure requires the introduction of several new variables. The Δbm value represents both the axial deformation and the rotation. Both values are determined by examining the building profile at the design drift, Δm and extracting the lateral deformation requirements and imposed rotation requirements. Determining the maximum rotation requirement imposed on braces used in the building may require significant computational effort. The engineer may prefer to select a reasonable value (floor drift), which can be demonstrated as a conservative value.

Each type of bracing is expected to be within the reeling performance values of the type of bracing selected for use in the project.

3.1 Purpose

The development of the test requirements of the AISC341-16 normative was motivated by a relatively small amount of test data on frames with bracings with restrained buckling available to construction engineers. In addition, there are no data on the response of these types of frames to high-intensity seismic movements. Therefore, the seismic performance of these systems is relatively unknown compared to conventional systems with braced steel frames.

The behavior of frames with bracings with restrained buckling differs significantly from conventional frames and other structural systems resistant to stresses from seismic movements. The factors that affect the performance of bracing under the stress of seismic movement are not well known and thus the requirements for testing are meant to ensure the operation according to the requirements of BRBs and also to develop knowledge of these systems.

Testing BRB specimens and BRB frame subassemblies is costly and time consuming. The test procedure must ensure that the prototype tested in accordance with the regulations in force, will function satisfactorily in a real seismic motion situation.

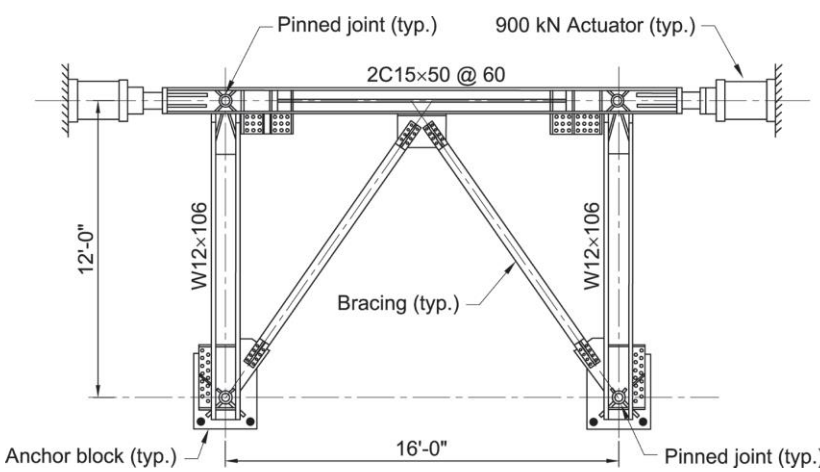

Fig. 3.1. Examples of BRB subassembly.

Regulations regarding the experimental qualification of BRBs should not lead to project-specific tests because, in most cases, the tests have been reported in the literature or provided by the manufacturer of BRBs and can be used to demonstrate that they meet the strength, deformation requirements and inelastic rotations. The regulations allow for the use of BRBs designed by manufacturers, by using a documented design methodology.

Most test programs are largely developed on tests in which the BRBs are axially loaded. However, regulations are being developed to develop testing of a subassembly that is subjected to a combination of axial loads and rotations. This reflects the idea that the ability of bracing to adapt to the required rotation requirements cannot be predictable only by analytical means.

If the conditions in the actual building differ significantly from the test conditions, additional tests are required that go beyond the requirements described in the regulations to ensure a satisfactory performance of the BRBs..

The plastic deformation of the BRB used in the development of the test sequence is necessary to determine the cumulative actual plastic deformation of the BRB. If the yield stress of the steel core was used to determine the test sequence and if the steel over-strength existed, the total plastic deformation requirement imposed during the test would be overestimated.

3.2 Testing of Subassemblies

The purpose of the subassembly tests is to verify the capacity of the bracings, in particular the deformation of the steel core and the behavior of the buckling-restraining mechanism, in order to adapt the combination of axial deformations and rotations without reaching failure.

Testing subassemblies is more difficult and expensive than testing uniaxial BRB specimens. However, the complexity of the behavior given by BRB due to the combined rotation and axial deformation requirements and the relative lack of test data on the performance of these systems indicate that testing of subassemblies and not only of specimens should be performed.

Subassembly testing is not required for each project. BRB manufacturers must perform tests for a reasonable range of axial loads, steel core configurations and other parameters, as required by applicable regulations. This data is expected to be available to design engineers later. Knowing the performance limits of the BRB minimizes the need to test subassemblies for each project.

A wide variety of subassembly configurations are possible for imposing axial deformation and rotation requirements on test specimens. Some potential subassemblies are shown in Figure 3.2. Subassemblies shall not include the joint between the beams and the posts provided that the tester reproduces, to a reasonable degree, the combined axial and rotational deformations expected at each end of the BRB. Rotation requirements can be concentrated in the area without the buckling locking mechanism of the steel core. Depending on the size of the rotation requirements, bending yield of the steel core may occur. Rotation requirements can also be adjusted by other means, such as tolerance in the non-adherent layer or in the buckling-restraining mechanism, elastic flexibility of the BRB and steel core, or by the use of spherical bolts or bearings. It is in the interest of the engineer to include in the testing of the subassembly all the components that contribute significantly to the satisfaction of the rotation requirements.

While upper extrapolation of the test scale is allowed for test specimens, the subassembly is not allowed to be on a much smaller scale than the prototype. It is expected that the subassembly test will be similar to the prototype and thus will provide a confirmation of the designed capacity to provide the necessary performance required by regulations.

It is intended that, for the tested subassembly, the axial capacity is greater than that of the prototype. However, it is possible for BRBs to be designed with much higher axial stresses. If the yield stress is so great that testing is impossible, the engineer is expected to make use of other alternative testing programs such as nonlinear finite element analysis, partial specimen testing, and small-scale testing, along with large-scale uniaxial testing, where appropriate or necessary.

The safety margin calculated for the stability of the steel core is a parameter that must be equal to or exceed the value of the prototype used. The method of calculating the stability of the steel core must be included in the design methodology.

The tested subassembly is required to be subjected, at the same time, to axial loads and rotations similar to those of the prototype. Identical BRBs located in different areas of the building will suffer maximum axial deformations and different rotations. In addition, the maximum values of axial rotations and deformations may be different at each end of the BRB. The engineer must make simplifying assumptions to determine the most appropriate combination for the rotational and axial deformation requirements of the test program.

Some test configurations require that one of the applied loads be fixed while the other load is varied. In such a case, the rotations can be applied and maintained to the maximum and the axial deformation applied depending on the required loading sequence. The engineer may consider it necessary to perform further tests on the same specimen in order to unify the results obtained from the tests.

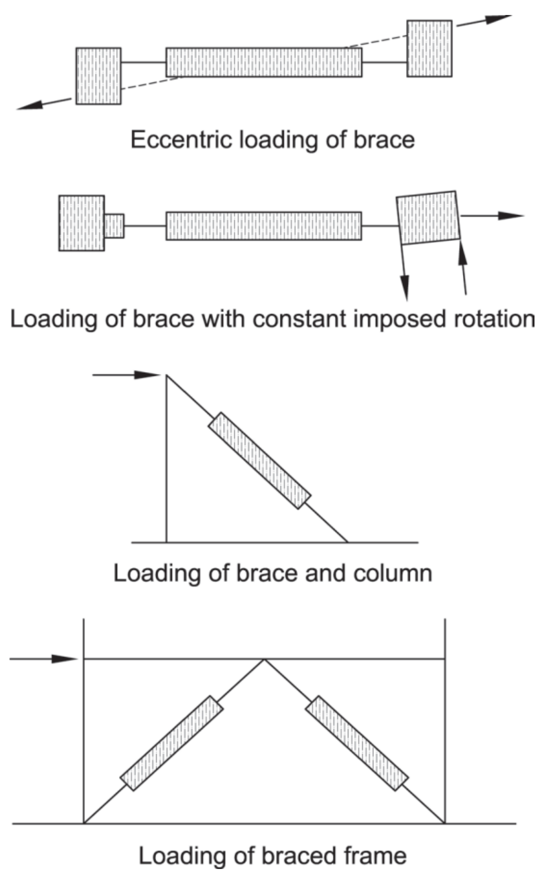

Fig. 3.2 Possible test subassemblies

3.3 Testing of Wind Bracing Specimens

The objective of testing BRB specimens is to establish the basic design parameters for BRB bracing frame systems.

The manufacturing tolerances used by BRB manufacturers to achieve the required performance may be stricter than those used for other steel structural elements. The engineer must not over-apply the regulations specified for the BRB, as the intent of the provisions is that the manufacture and supply of the BRBs is accomplished through a performance-based process.

It is considered sufficient that the manufacture of the test specimen and prototypes be performed using the same control and quality assurance procedures and that they should be designed using the same design methodology.

During the planning stages of either a subassembly test or an uniaxial test, there may be certain conditions that cause the test specimen to deviate from the parameters set out in the test regulations. These conditions may include:

• Lack of availability of beams, columns and BRBs at dimensions that correspond to the actual dimensions to be used in the actual frame of the building.
• Limiting laboratory trial settings
• Transport and construction site constraints

The cases in which such deviations are acceptable are specific to each project. For these specific cases, it is recommended that the specialist engineer demonstrate that the following objectives are met:

• Reasonable test scale
• Similar design methodology
• Adequate power of the test system
• Stable buckling fastening to the steel core of the prototype
• Adequate rotation capacity in the prototype
• Adequate capacity of the deformations accumulated in the prototype

In many cases, it is not practical or reasonable to test the exact joints present in the prototype. In general, the requirements for joining the steel core to the frame bracket of which the BRB is a part are well defined due to the known axial capacity of the BRB and the limited bending capacity of the steel core. Subsequent design of bolt, screw or weld joints is in itself a complicated issue and this topic is not intended to be the focus of the test program.

The purpose of these provisions is to ensure that the joints at the ends of the BRB reasonably represent the prototype joints. It is possible that, due to manufacturing or assembly constraints, mounting constraints, mismatches for bolt holes or screws may occur. In some cases, such variations are not detrimental to the qualification of a cyclical test. Acceptance of joint variations is based on the opinion of the specialist engineer who coordinates the testing.

3.3 Test and Measurement Equipment

When performing the tests, a reaction frame equipped with equipment for loading, measuring and automatic data acquisition was used. Figure 3.3 schematically shows the main characteristics (dimensions, capacity of hydraulic cylinders) of the reaction frame. The endowment of the laboratory, worth approximately $ 1 million, was made through a donation made by the Japan International Cooperation Agency (JICA) within the Romanian-Japanese seismic risk reduction project.

The elements were subjected to alternating cyclic side loads, applied statically. The horizontal forces were applied by means of two cylinders with a capacity of 100t. The control was performed on drifts throughout the test. No axial forces were applied.

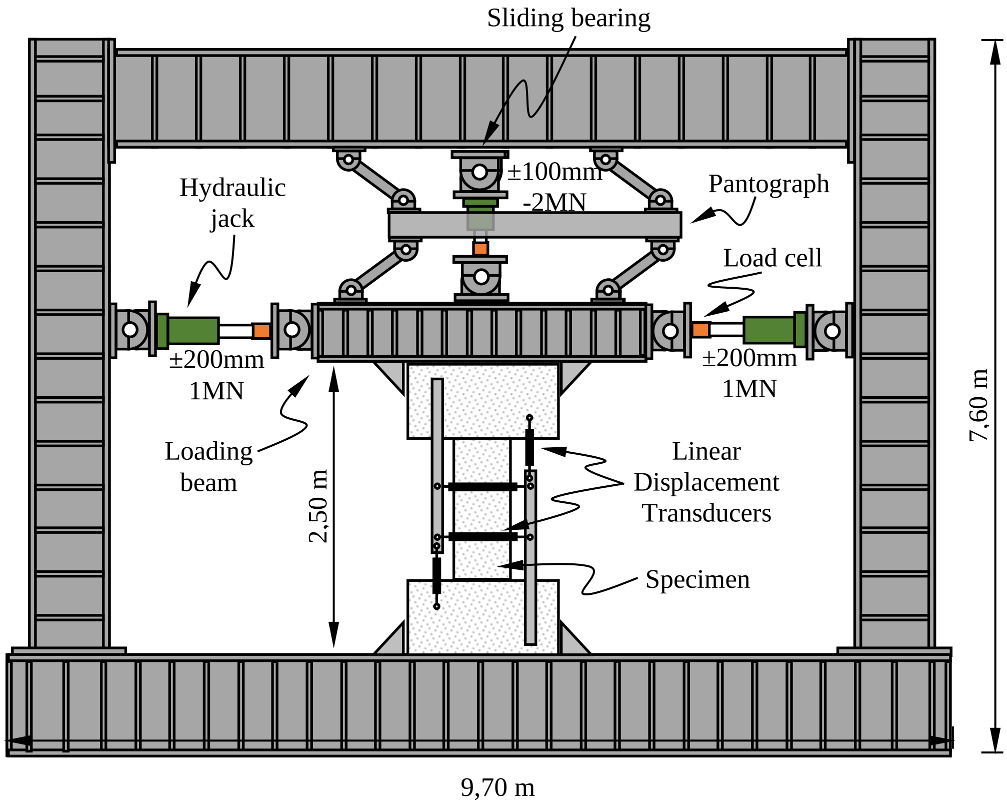

Fig.3.3 – The reaction framework used to test the BRBs

The positioning of the BRB prototype was on diagonal and is schematically represented in fig 3.3 and fig.3.4.

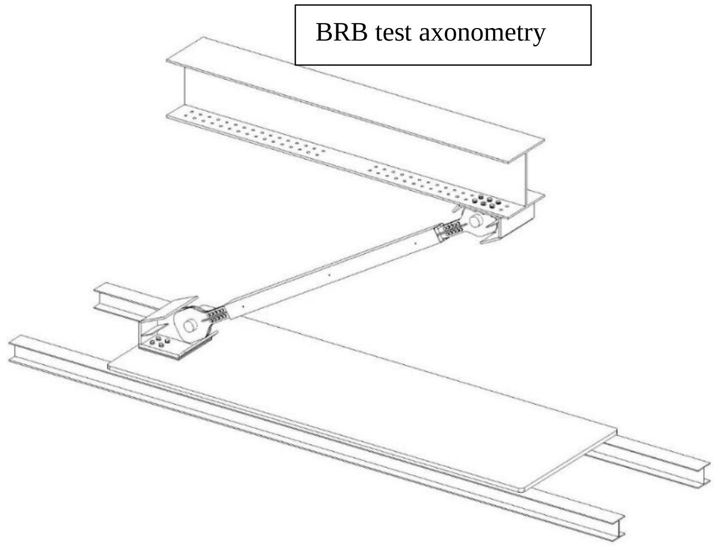

Fig. 3.4 – Axonometric seismic test frame of BRB prototypes

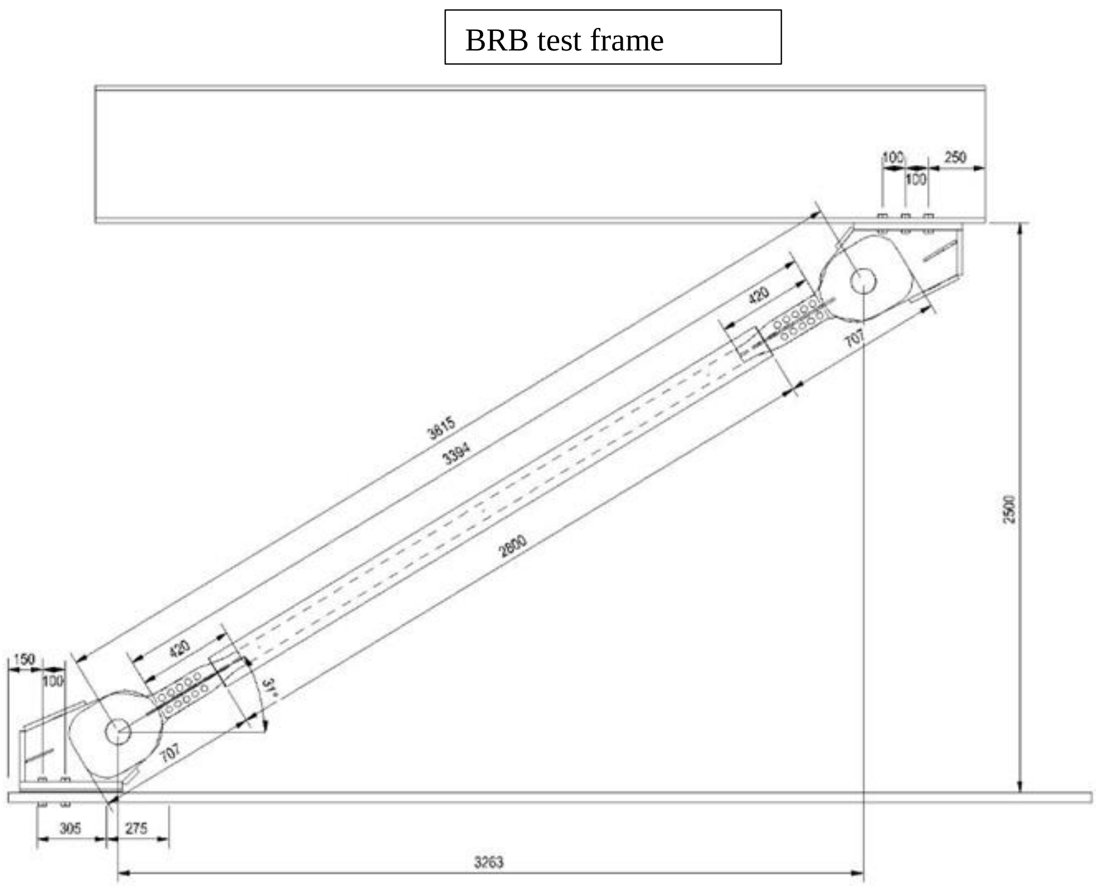

Fig. 3.5 – BRB prototype test frame dimensions

The BRB prototype was mounted in a temporary position with the help of the bolt at the bottom and was lifted and mounted on the test position with the help of manual chain blocks with which the test frame is equipped. The assembly steps are illustrated in fig. 3.6 ÷ 3.9.

Fig. 3.6 – Seismic frame and BRB prototype elements

Fig. 3.7 – Mounting in the test position of the BRB prototype

Fig. 3.8 – Mounting in the test position of the BRB prototype

Fig. 3.9 – Mounting in the test position of the BRB prototype

4. LOADING SEQUENCE

The loading sequence requires that each BRB tested reach the corresponding ductilities up to 2 times greater than the floor drift and a cumulative axial inelastic deformation capacity of 200 times the flow deformation. Both requirements are based on a study in which a series of nonlinear dynamic analyzes were performed on building models to investigate the performance of this system. The requirement for ductility capacity is an average of the test response values (Sabelli et al., 2003). The cumulative ductility requirement is significantly higher than expected for the code earthquake, but testing of BRBs showed that this value is easy to achieve. It is expected that as more test data and construction analysis results become available, these requirements will be reviewed.

The ratio between the yield deformation of the BRB, Δby, and the deformation corresponding to the floor drift at the SLU, Δbm, must be calculated to define the test protocol. This ratio is the same as the ratio between the drift amplification factor (defined by the regulations in force) and the real over-resistance of the BRB;

Engineers should note that there is a minimum BRB deformation requirement, Δbm, corresponding to 1% of the floor drift. If the overcurrent is provided in excess of that required by the BRB to limit the design floor drift, it may not be used as a basis for reducing the test protocol requirements.

It is necessary to test this minimum at least twice (2% floor drift).

For example, it is assumed that the deformation of the BRB corresponding to the design floor drift is four times greater than the deformation at flow. It is also assumed that the design floor drift is greater than the minimum of 1%. To calculate the cumulative inelastic deformation, the cycles are converted from multiples of the BRB deformation to the design stage drift, Δbm, to multiples of flow deformations, Δby. Because the cumulative inelastic drift at the end of the 2Δbm test cycle is less than the minimum of 200Δb and it is necessary for BRB tests to perform additional cycles up to 1.5Δbm. At the end of four such cycles, the need for cumulative inelastic deformations was reached.

Regulations do not require dynamically applied tasks. The slow application of cyclic loads is widely described in the literature for tests with BRB specimens, and is accepted in the AISC341-16 standard. It is recognized that dynamic loading can significantly increase the cost of testing and that there are few laboratories with the ability to apply dynamic loads to large-scale test specimens. Moreover, available research on the dynamic loading effects on steel test specimens has not demonstrated a need for such tests.

If it is considered that the effects of the loading speed are potentially significant for the steel core and for the material used in the prototype, it is possible to estimate the expected behavior change by performing tests at low speed (cyclic test) and high speed (dynamic loading in the earthquake).

The loading cycles for the BRB prototypes were determined using the floor drift limited to 2% and are shown in fig. 4.1. The seismic frame was operated horizontally to obtain the desired axial deformations. The loading protocol of the frame in the horizontal direction is shown in fig. 4.2.

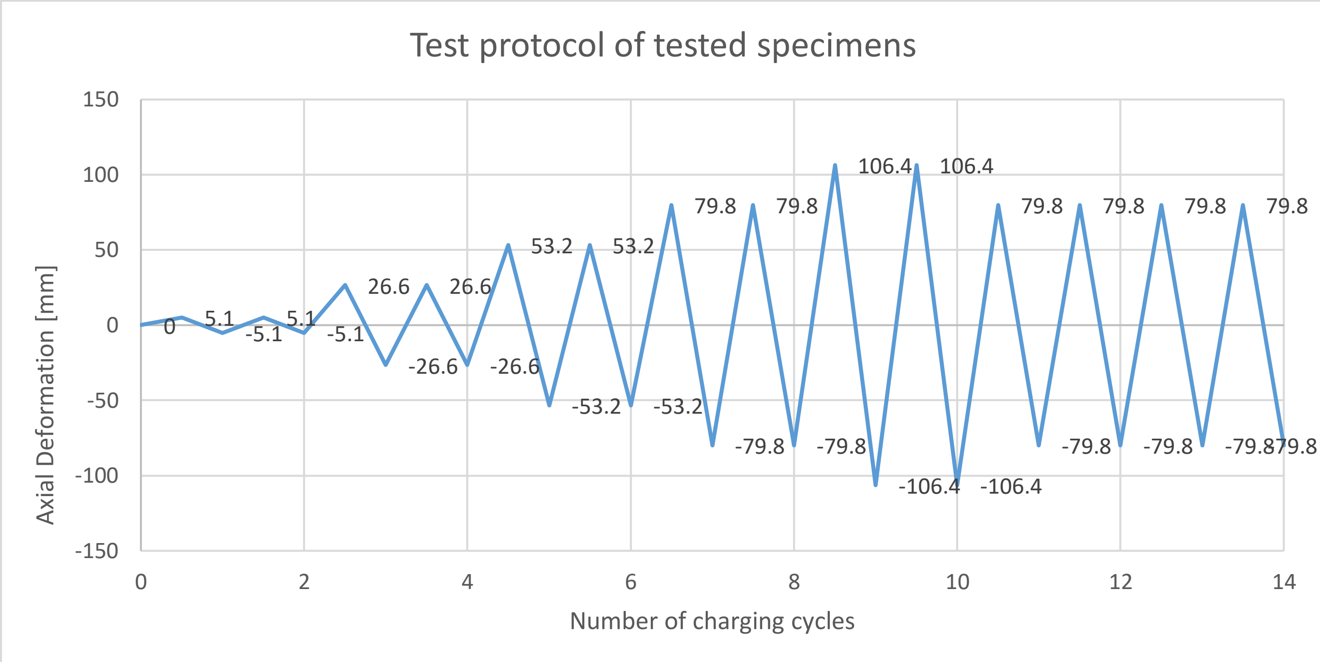

Fig. 4.1 – Test protocol of tested specimens [Axial deformation]

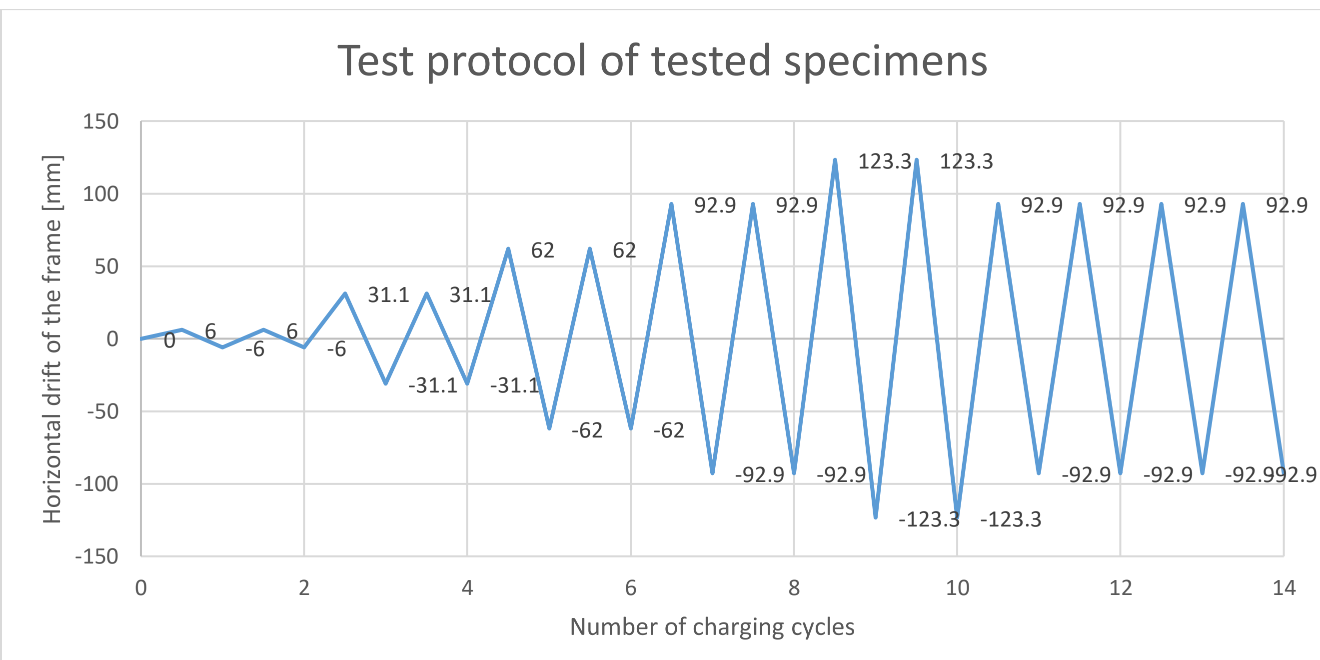

Fig. 4.2 – Test protocol of tested specimens [Horizontal seismic frame deformation]

5. INSTRUMENTATION

The minimum instrumentation requirements are specified in AISC 341-16 normative to allow for the determination of test-specific information. An alternative instrumentation is expected to be appropriate for some specific cases. The displacement measurement for the studied specimens was performed with the help of inductive displacement transducers. The operation of the transducers is based on the principle of the magnetic circuit. The transducers supply voltages at the output, which are generated by the movement of a conductor in the magnetic field by induction. The magnetic field must change with a certain frequency and the displacement of the conductor appears as an amplitude modulation (the amplitude of the alternating voltage changes with the displacement). For the test specimens in the CNRSS laboratory 7 rectilinear displacement transducers were installed. The surface on which the transducers operate was made of glass in order to have a flat surface and not to have interferences in the process of measuring displacements. The transducers were installed according to the diagram in figure 5.2 and count the rectilinear displacements as follows:

- Transducer 1- Maximum stroke -100mm - horizontal displacement for the upper beam of the seismic frame
- Transducer 2- Maximum stroke -100mm - horizontal displacement for the upper beam of the seismic frame
- Transducer 3- Maximum stroke ± 50mm - axial displacement between the steel core and the outer tube of the BRB at the upper end
- Transducer 4- Maximum stroke ± 50mm - axial displacement between the steel core and the outer tube of the BRB at the upper end

- Transducer 5- Maximum stroke ± 25mm - vertical displacement for the upper beam of the seismic frame
- Transducer 6- Maximum stroke ± 25mm - horizontal lateral displacement at the lower end of the metal pipe
- Transducer 7- Maximum stroke ± 25mm - horizontal lateral displacement at the lower end of the metal pipe

Fig. 5.1 – Assembly of transducers for the BRB prototype

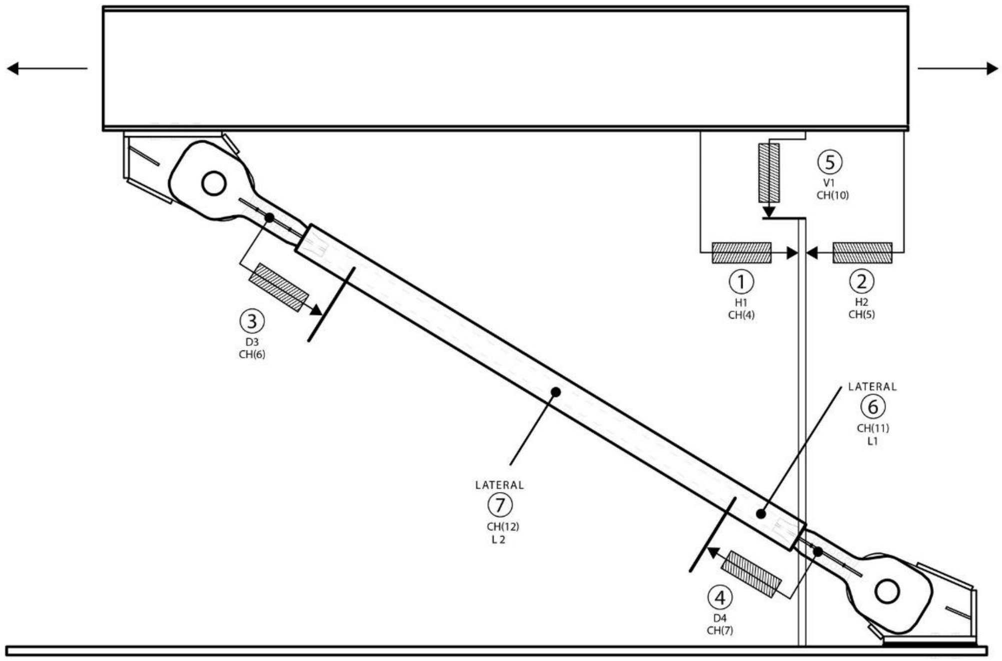

Fig. 5.2 – Assembly of transducers for the BRB prototype

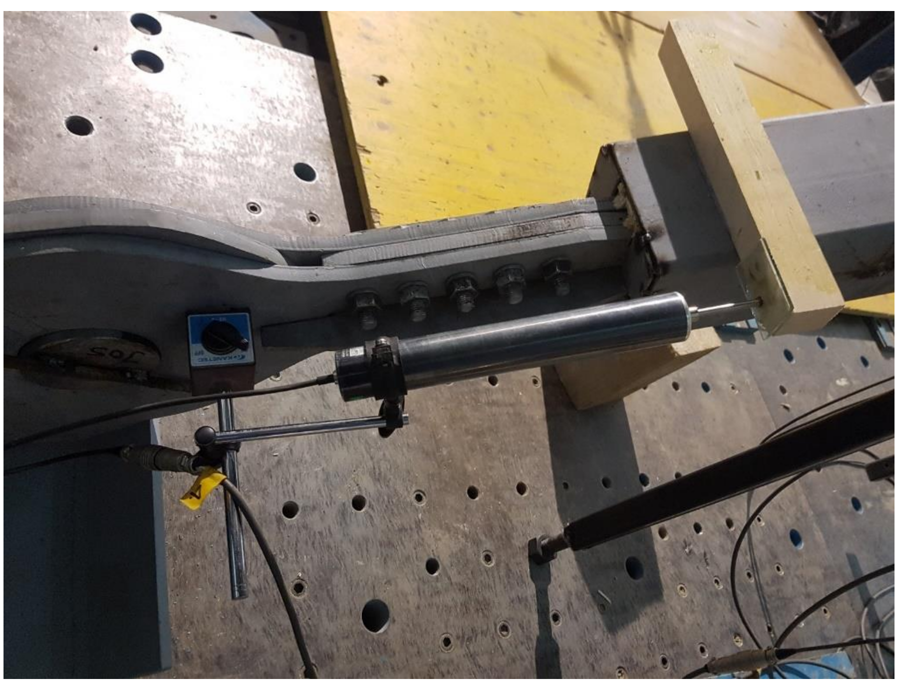

Fig. 5.3 – Assembly of transducer no.4

Fig. 5.4 – Assembly of transducer no.6

Fig. 5.5 – Assembly of transducers no.1, no.2 and no.5

Fig. 5.6 – Assembly of transducers no. 1, no. 2 and no. 5

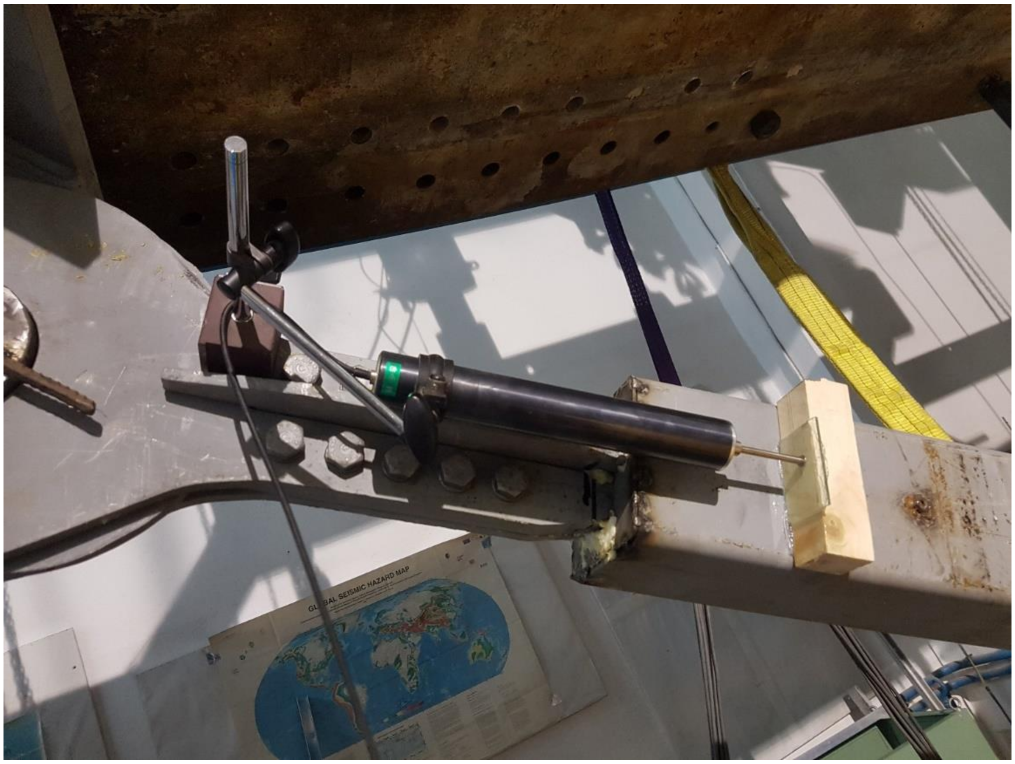

Fig. 5.7 – Assembly of transducer no.3

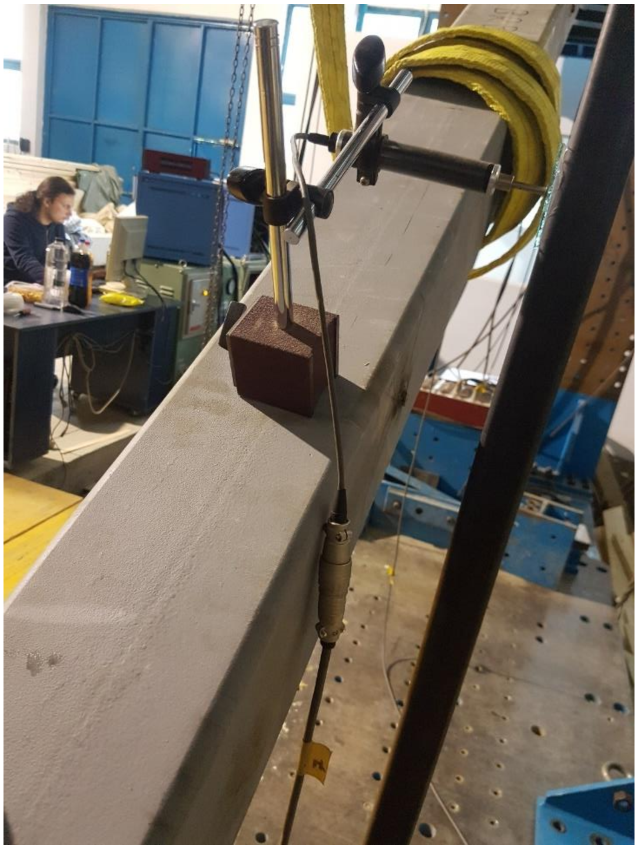

Fig. 5.8 – Assembly of transducer no.7

Fig. 5.9 – Assembly of transducer no.4

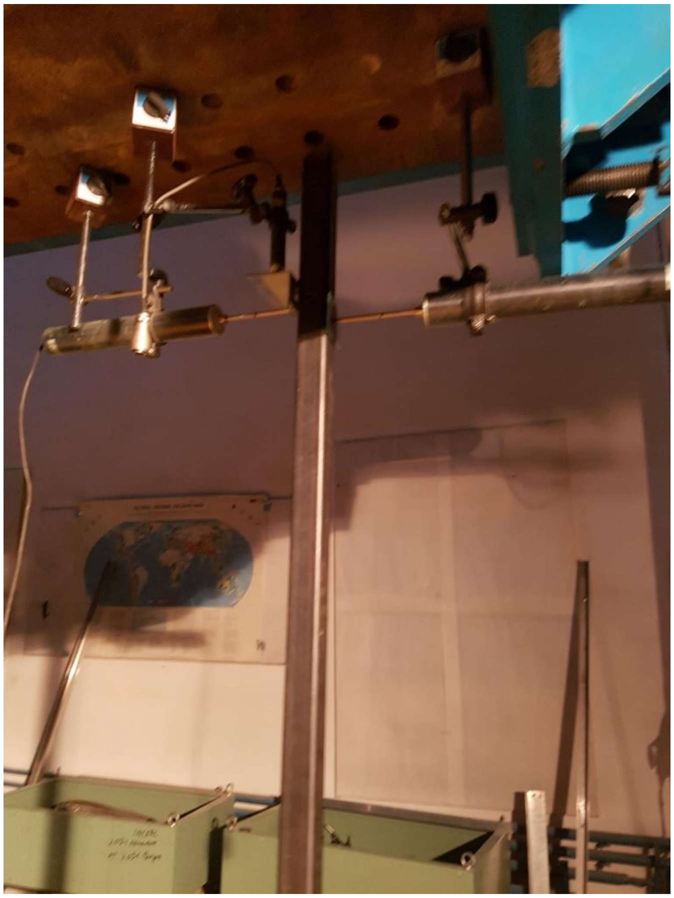

Fig. 5.10 – Assembly of transducers no.1, no.2 and no. 5

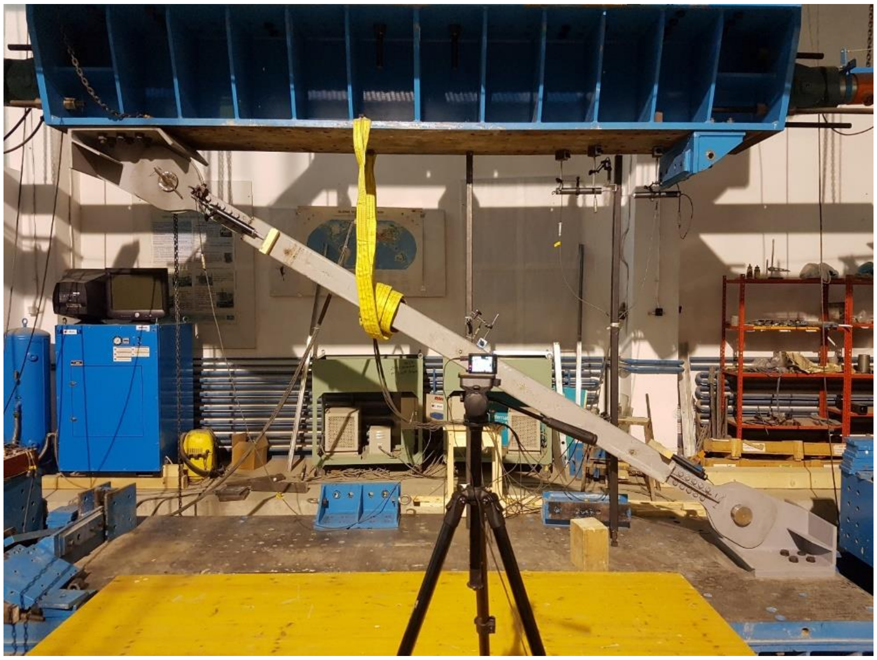

Fig. 5.11 – Assembly of transducers for the BRB specimen

6. MATERIAL TESTING REQUIREMENTS

Testing of the material of the steel core used in the manufacture of the test samples is required. In general, there was a close link between the results of tensile test specimens and the tensile effects of large-scale uniaxial BRB tests.

5 standardized tensile test pieces were made of the same steel plates as those from which the BRB steel core was made. Extensometers were installed on the specimens to measure elongations during testing. The tests were performed in the Construction Materials laboratory within the UTCB Framework. The standardized test pieces made have a rectangular section presenting a calibrated section and two ends for the clamps in the tanks of the test press. During these tests, the yield strength and yield strength of the steel were determined. The shape of the characteristic curve obtained is specific for the case of materials with yield bearing, the steel used being S275. The rupture was made by cooking the tested section. The results of the traction tests are:

$$f_{y,m} = 280N/mm^2$$
$$f_{u,m} = 440N/mm^2$$

$$\varepsilon_{y,m} = 0.2\%$$
$$\varepsilon_{u,m} = 34.8\%$$

where:

- $f_{y,m}$ = measured yield limit of standardized test specimens
- $f_{u,m}$ = measured breaking limit of standardized test specimens
- $\varepsilon_{y,m}$ = specific elongation of the measured yield of the standardized test specimens
- $\varepsilon_{u,m}$ = the specific elongation of the measured rupture of the standardized test specimens

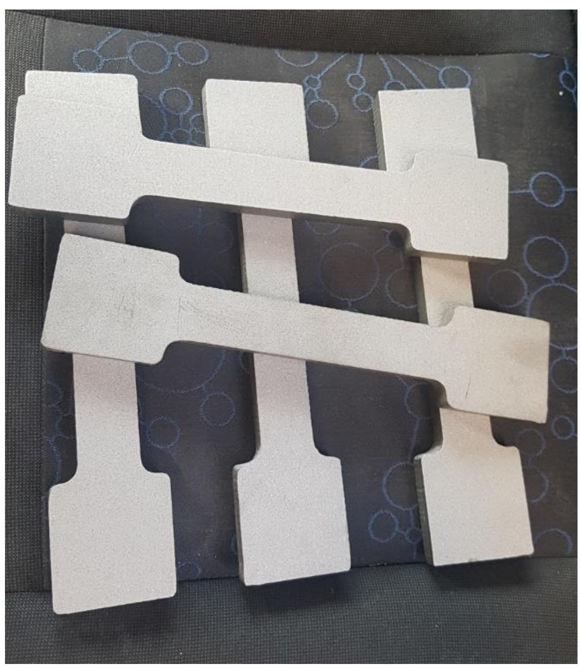

Fig. 6.1 – Specimens for tensile testing of BRB steel core material

Fig. 6.2 – Tensile testing of standardized specimens

Fig. 6.3 – Tensile testing of standardized specimens

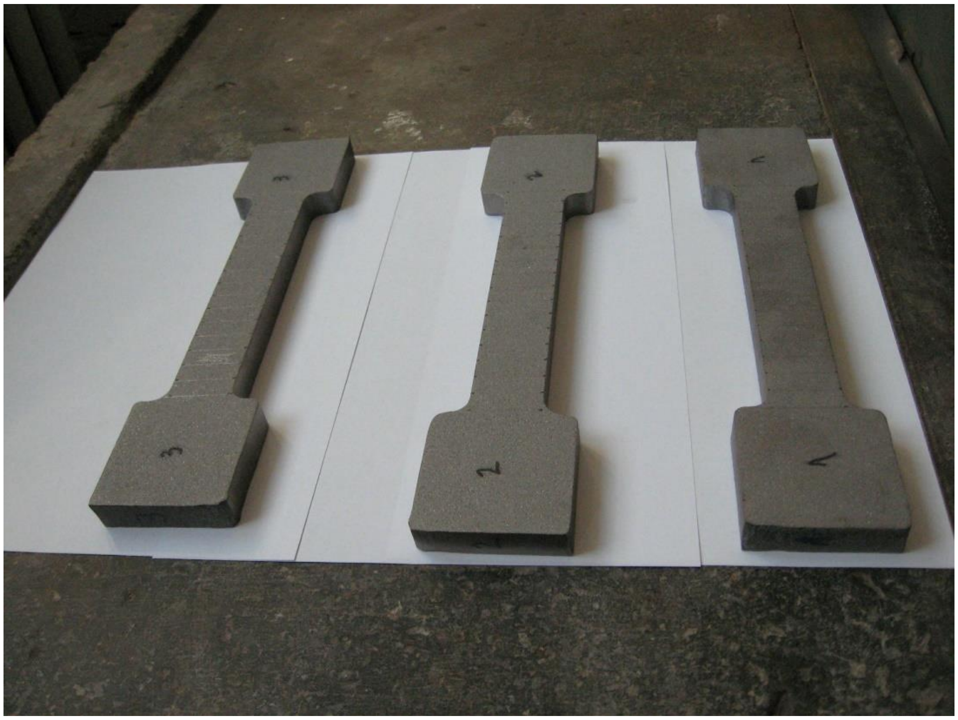

Fig. 6.4 – Marking of parts on test specimens for tensile testing

Fig. 6.5 – Tensile test specimens

7. VALIDATION OF TEST RESULTS

The reported results are required to demonstrate compliance and to determine the steel reinforcement requirements and to determine the compressive strength. Nonlinear modeling is becoming more developed and more frequently used so that the production of test data for the calibration of nonlinear modeling of elements becomes an important function. There is little data on the behavior of BRBs beyond their design range; such information may be useful in verifying the security of the system.

The acceptance criteria shall be such that the minimum test data to be transmitted shall consist of at least one subassembly test or at least one uniaxial test. In many cases the test sample for subassemblies also qualifies as a test specimen for BRB. If a specific test is performed on a particular subassembly design, the simplest method is to perform two subassembly tests to meet the requirements of this section. These requirements can be met by a single tested subassembly incorporating, for example, two bracings arranged in a chevron-type configuration or other type of configuration.

BRBs are considered to be experimentally qualified when they meet the following conditions at the end of the test protocol:

- the tested specimen has a stable cyclic behavior
- the maximum tensile and compressive forces must be greater than the flow resistance of the BRB, for all deformation cycles greater than Δby
- the ratio between the maximum compressive force and the tensile force must be less than 1.3, for all deformation cycles greater than Δby
- no failure of the joints, global buckling of the BRB or rupture of the steel core

Depending on the means used to join the subassembly test specimen or the test apparatus and instrumentation system used, slipping of the load screws may occur and may be reflected in the displacement history graph. These may appear as a series of descending peaks reflected in the applied effort and are generally not a cause for concern, provided that the behavior does not adversely affect the performance of the BRB or its joint.

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