Experimental and numerical validation of the technical solution of a brace with pinned connections for seismic-resistant multi-story structures

Ramona Gabor, Cristian Vulcu, Aurel Stratan, Dan Dubina
Politehnica University of Timisoara, Romania

Florin Voica, Dragos Marcu, Dragos Alexandrescu
Popp&Asociatii, Bucharest, Romania

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SUMMARY:
Concentrically braced frames represent a convenient structural typology for multi-storey buildings located in high-seismicity areas, offering a good strength and stiffness. The present paper presents the technical solution of 29 storey building located in Bucharest, Romania, with a mixed lateral force resisting system: reinforced concrete shear walls and steel braces. It is concerned with the experimental and numerical validation of seismic performance of brace connections on one hand, and of the overall brace assembly on the other hand. A connection with gusset plates and pin was adopted. One of the brace connections uses an eccentric pin, allowing for variation of the pin-to-pin length, which facilitates erection on one hand, and allows compensation for axial forces in braces due to gravity loads on the other hand. High strength steel was used for gusset plates and the pin in order to keep dimensions to a minimum. Preliminary finite element simulations have shown that the buckling plane of the brace is undetermined (the buckling strength in the plane of the connection and out-of plane are similar), due to the fact that the brace is made of a circular hollow section. Due to peculiarity of the connection, finite element analyses and experimental tests were performed in order to validate the cyclic performance of the connection and the brace. Four tests were performed on a scaled model of the brace, for two different pin-to-pin lengths.

Keywords: steel brace, eccentric pin, high strength steel, buckling, finite element analysis

1. INTRODUCTION

For the multi-storey buildings, located in high-seismicity areas, steel concentrically-braced frames (CBF) are stiff with a reasonable ductility level and represent a convenient structural typology for this type of buildings. The main components of the CBF, i.e. braces make the subject of the current paper. The analysed braces are components of a building with 2 basements and 29 levels above ground, measuring a total height of 117.6 m, named “Smart Park”, situated in Bucharest, Romania. Main structural system consists of steel frames, reinforced concrete cores and concentrically braced steel frames. A general overview of the structure is presented in Fig. 2.

The braces are realised from circular hollow section tubes and pined connections. In relation to the brace length, two situations are found within the structure:

- Brace with length covering two storeys (see Fig. 2a).
- Brace with length covering one storey (see Fig. 2b).

The connection of the braces is realised as pinned using gusset plates and pins (see Fig. 3.). For this type of connection two types of pins were used: at one end a pin with constant section, and at the other end a pin with variable section. The advantage of using an eccentric pin is given by the possibility to increase or decrease the actual length of the brace allowing for an easier erection of the structure. The effect of the permanent loading is also reduced by placing the braces after the erection of the structure and the concrete cast into the slabs.

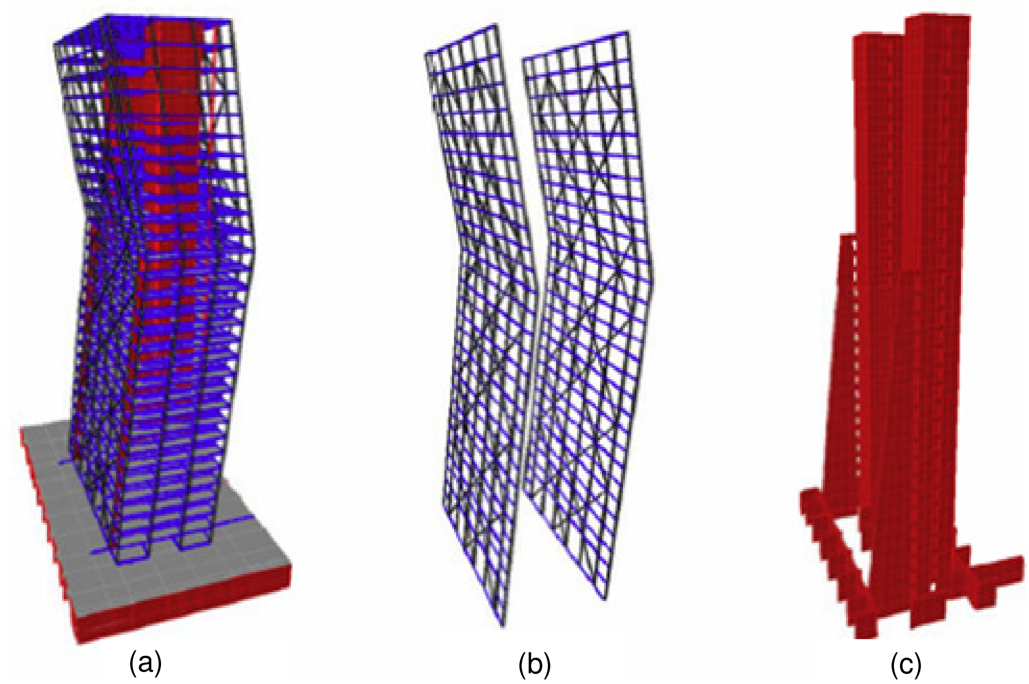


Figure 1. Structural systems of the building Smart Park: a) tower structure, b) diagonals in east-west direction, c) concrete cores in north-south direction

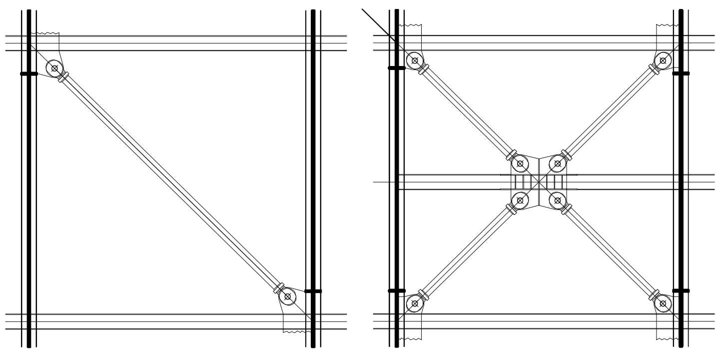


Figure 2. Brace configurations in the analysed structure: brace covering two storeys (a) and one storey (a).

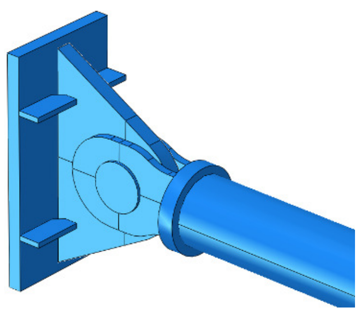


Figure 3. Pinned connection of the brace

The structure was designed according to P100-1 (2006) and EN 1993-1-1 (2004). The connections were designed according to EN 1993-1-8 (2004). In order to have a confirmation of the adopted solution, experimental tests were needed for validation. Therefore, a series of numerical simulations and experimental tests were performed. The lengths of the braces within the structure were 4200 mm and respectively 9300 mm, covering the following cross sections obtained from design: D244.5x25, D244.5x20, D219.1x20, D219.1x16 and D219.1x10.

Considering the testing facility, the tests were performed on scaled braces, i.e. length of 2700 mm and respectively 5900 mm, both braces having a cross section of D139.7x6.3. The equivalence between the designed braces and the tested braces was performed considering the same class cross-section and slenderness.

The behaviour assessment of the braces followed two directions: finite element analysis and experimental analysis. Several detailing solutions for the connections were considered and tested numerical, until the proper connection configuration was established. Both analyses were performed in order to study the response of the braces under compression and tension loading (FEM), and cyclic loading (experimental).

2. PRE-TEST FINITE ELEMENT ANALYSES

In order to anticipate the behaviour of the braces assemblies, pre-test finite element analyses have been performed with the finite element software Abaqus (2007). In the first instance the connections were analysed to evaluate the component behaviour under tension and compression loading. Secondly, the brace assembly was subjected to FE analysis, to see also the buckling of the brace especially due to the fact that the brace cross-section is double symmetrical.

2.1. Connection

To model the connections, solid elements have been used. For the material definition the stress-strain curves using the nominal values of material characteristics have been introduced. Solid elements were used with a mesh of linear hexahedral elements C3D8R type. A dynamic explicit analysis was used for all models. The load was applied through displacement control applied in one of the supports, and considering the other support fixed. The investigation of the connections with FE models followed several steps, aiming to evaluate the stress distribution and plastic deformations through the connection components. Fig. 4 presents the geometry of the connection. Several components can be observed within this connection: two external gussets (each of 34 mm), central gusset (38 mm), two reinforcements (15 mm) welded on the central gusset and the pin – eccentrically and constant.

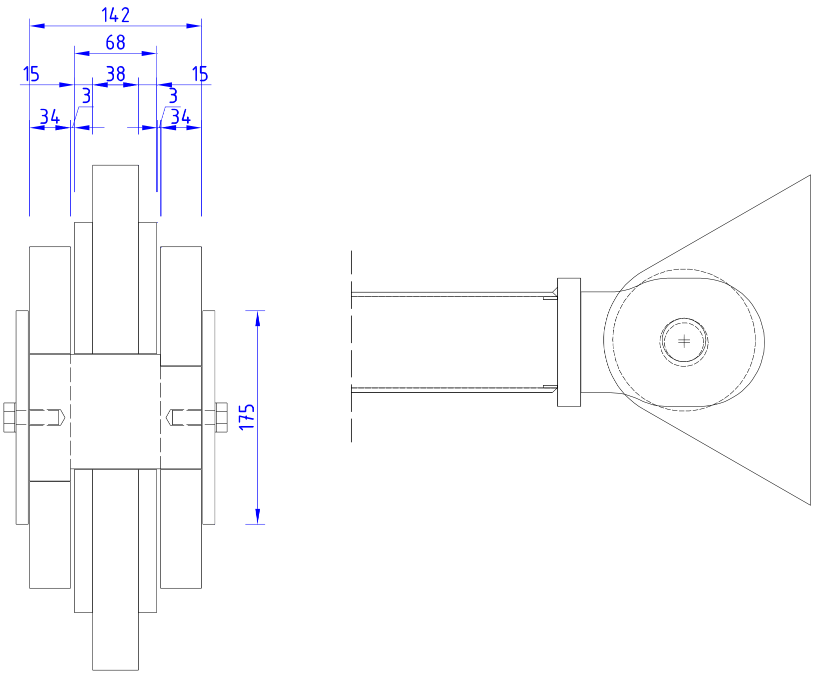


Figure 4. Connection cross-section and geometry

Grade S690Q steel was used for pins, and S460N for the gussets and reinforcements. Nominal material properties were used. The response of the connection was observed when the applied force was equal to the plastic capacity of the brace, estimated using a material overstrength factor of 1.25. Minor plastic strains were observed in the pin and gusset plates of both connection with eccentric pin (Fig. 5b), and connection with constant pin (Fig. 5d).

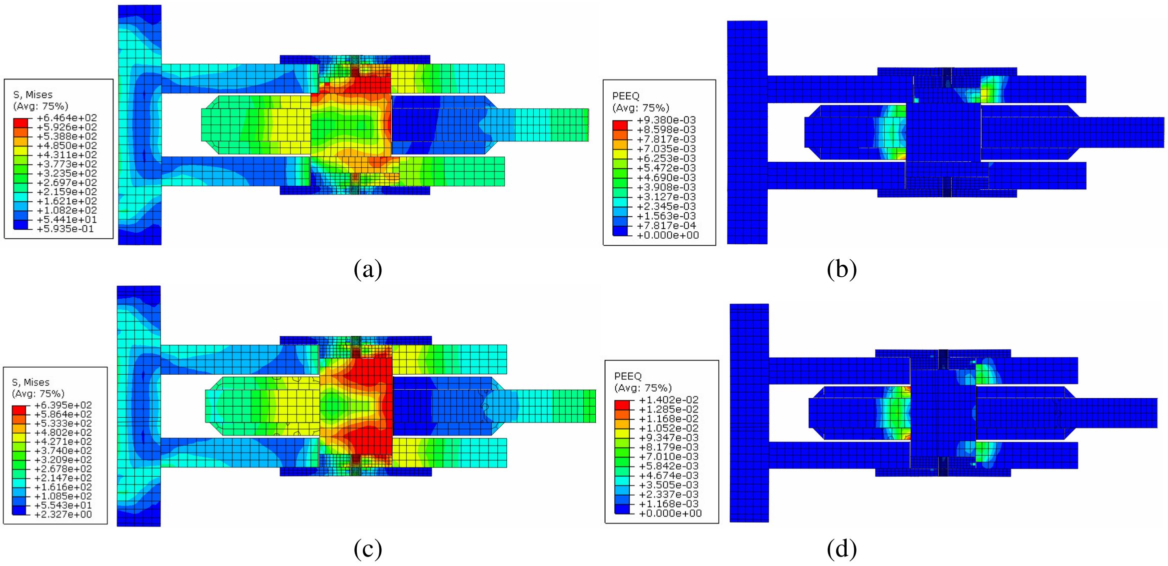


Figure 5. von Mises stresses (a), (c) and equivalent plastic strains distribution (b), (d).

A third connection solution with thinner gusset plates was analysed, using for the gussets and pin S690Q as base material. The results evidenced reduced improvements, with no significant differences in terms of von Misses stress and equivalent plastic deformation. Table 2 summarises the results for the three specific connections.

Table 2. Maximum values for von Mises stresses and equivalent plastic stains

Model	Pin		Lateral gusset		Central gusset (&reinforcement)	
	σ_e	ε_{pl}	σ_e	ε_{pl}	σ_e	ε_{pl}
219x10-ecc	646.4	0.00527	464.0	0.00720	465.2	0.00938
219x10-ct	639.5	0.00399	464.7	0.00800	471.2	0.01402
219x10-ct-690	638.9	0.00304	464.6	0.00772	706.2	0.00430

Based on the obtained results, the connection adopted further within the numerical models of the brace assemblies and experimental specimens, the reinforcements were removed using instead a central gusset with equivalent thickness. The base materials for the connections were: S690Q (gussets), and for pins an low alloy steel containing nickel, chromium and molybdenum with f_y=785 N/mm^2 and f_u=980 N/mm^2, known for its toughness and capability of developing high strength in the heat treated condition while retaining good fatigue strength. The components are presented in Fig. 6.

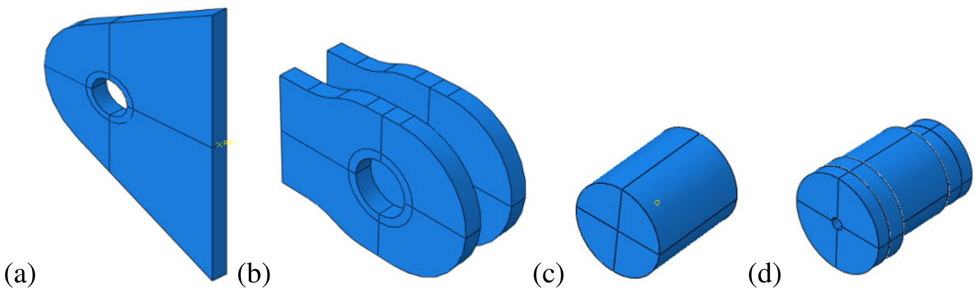


Figure 6. Connection components: a) central gusset; b) lateral gussets; c) constant pin; d) variable pin.

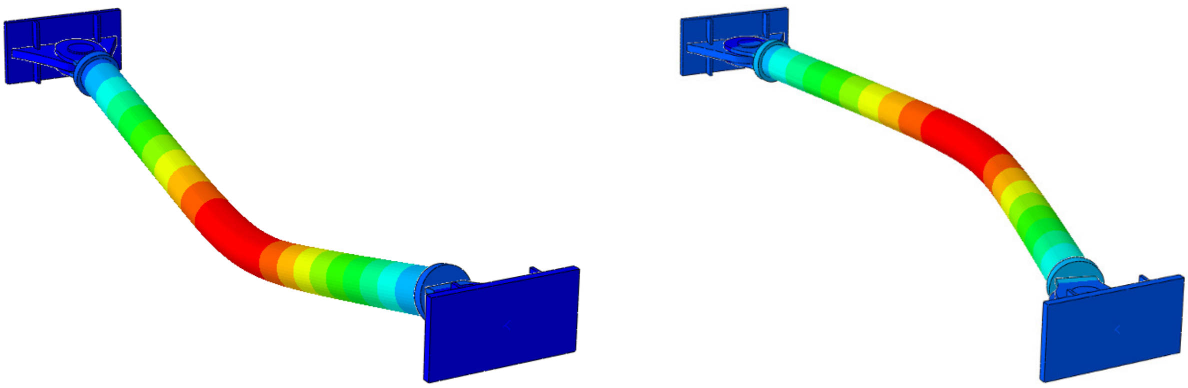
2.2. Brace assembly

The complete brace assemblies were investigated in order to assess their behaviour under tension and compression, and most special to foresee the buckling mode of the tubular hollow section. Here, the same models as for the experimental program have been investigated: the short model with 2700 mm length and the long model with 5900 mm length. The numerical model of the brace assembly contained, besides the two connections (with constant and variable pin) studied separately, also the brace itself. For the assembly a combination between solid elements (connections) and shell elements (brace circular hollow section) was used. The mesh was defined by using linear hexahedral elements of C3D8R type for solid elements, and S4R type for the shell elements.

It is to be noted that the FEM analyses of the brace assembly were performed before the experimental testing of the actual braces. The numerical model of the brace with 2700 mm length subjected to compression showed a low difference in terms of maximum compression strength between the brace model with free deformation in all directions, brace model with constrained out-of plane displacements (Fig. 7a), and constrained displacements in the plane of the connection (Fig. 7b) – see also Table 2.

Table 2. Compression resistance of brace assembly of 2700 mm length

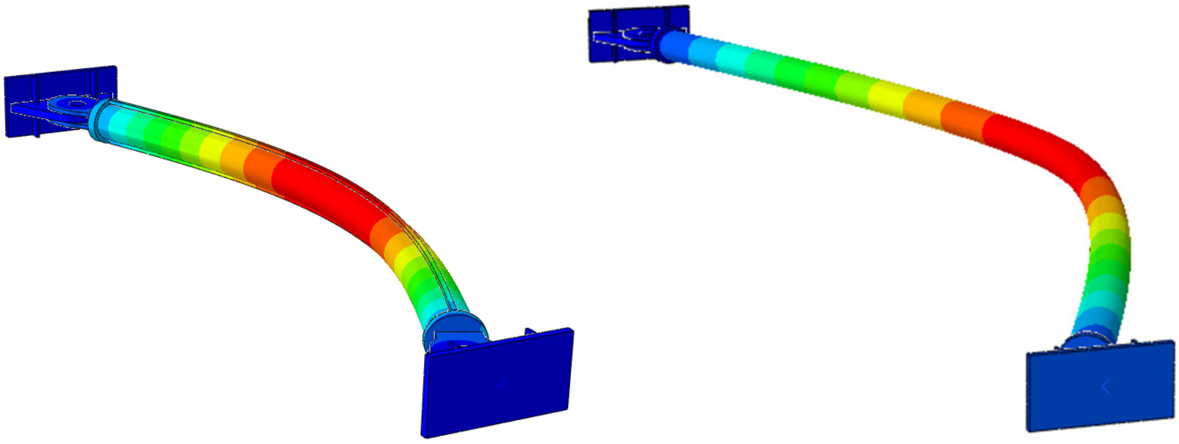
Model	2D139x6_A_MC2	2D139x6_A_MC2_By	2D139x6_A_MC2_Bz
In plane displacements	free	blocked	free
Out of plane displacements	free	free	blocked
Compression resistance, kN	936.0	1041.0	1007.3



(a) (b)

Figure 7. Brace deformation of the model with in plane displacements blocked (a) and of the one with out of plane displacements blocked (b).

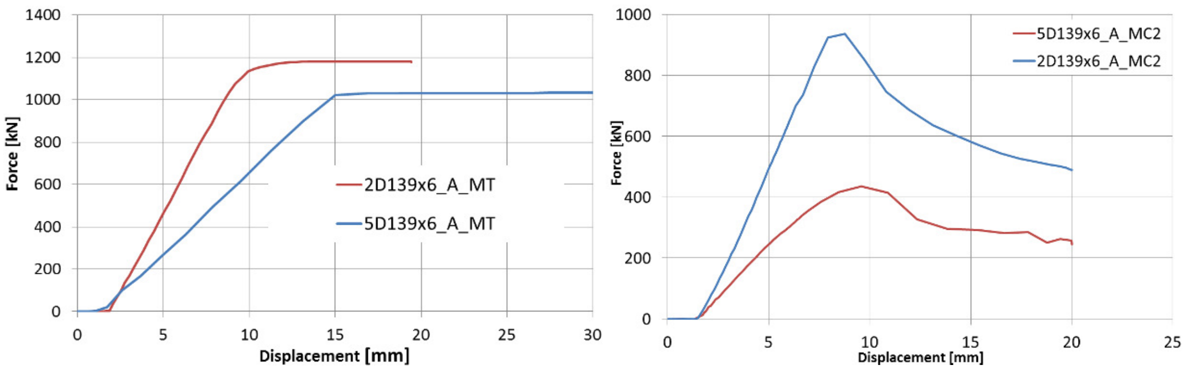
It is known that because of the double symmetry of the tubular hollow section, the brace is sensitive to buckling in all directions, situation that is not convenient. To control the in plane buckling, a 4 mm eccentricity was adopted in the brace plan between the hollow section brace axis and the midpoints of the lateral gussets. Additionally, a set of numerical models of the brace with 2700 mm length were analysed, containing the 4 mm eccentricity at the supports as well as a global brace imperfection of L/500 which was oriented in the connection plane – in the same direction with the 4 mm eccentricity, and in opposite direction with the 4 mm eccentricity, and also in out-of plane. It was observed that the 4 mm eccentricity were not enough to keep the deformation of the brace assembly in the plane of the connection, assuming the global brace imperfection in out-of plane direction, representing the situation with high probability for triggering out of plane buckling of the brace. Therefore, due to the fact that the brace specimens were already fabricated, it was decided to come with a solution to this problem, i.e. one of the braces with 2700 mm length was improved by increasing the cross-section properties of the brace on the out-of plane direction through the use of two stiffeners (14x14 mm) welded along the entire brace length. The adopted solution improved the behaviour of the brace, i.e. the deformation occurred in the plane of the connection as can be seen in Fig. 8a. For the braces with 5900 mm length, the same study was performed, and it was observed that stiffeners were not necessary due to the fact that the deformation of the brace took place in the plane of the connection (see Fig. 8b)



(a) (b)

Figure 8. Deformation of the 2700 brace with stiffeners (a), and 5900 brace (b).

The behaviour of the two braces (2700 and 5900 mm length), in terms of force-displacement curves, is presented for both tension (Fig. 9a) and compression (Fig. 9b).



(a) (b)

Figure 9. Force-displacement curves for the braces subjected to tension (a), and for the braces subjected to compression (b).

3. EXPERIMENTAL PROGRAM

The experimental program included 4 braces subjected to cyclic loading. Due to limitations of space and testing equipment, scaled specimens have been used, but with the same class for the cross section (class 1), and non-dimensional slenderness ($\overline{\lambda}$=0.75 and 1.64) close to the one of braces used in design. Figure 10 shows the experimental setup.

Specimens are presented in Table 3. Specimen SP27-1 was tested as designed; to specimen SP27-2 two steel bars 14x14 mm were welded on brace to change the symmetry of the circular cross-section. This action resulted from the behaviour of the first specimen, which buckling took place out-of-plane, situation that is not convenient. The other two specimens (SP59-1 and SP59-2) were tested with no changes in comparison with the design solutions.

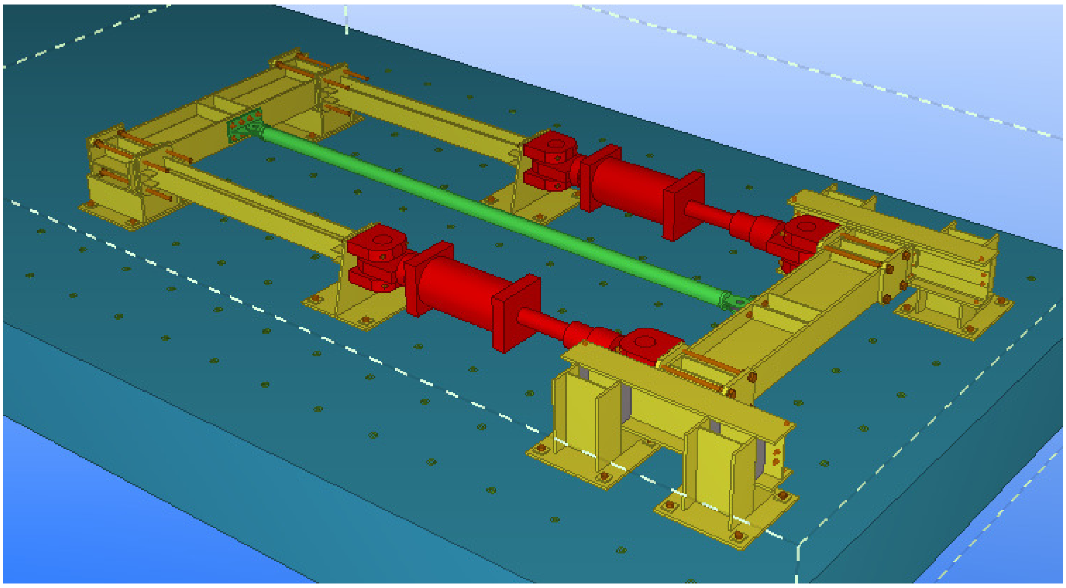


Figure 10. Test set-up.

Table 3. Tested specimens to cyclic loading

Specimen	Pin to pin length [mm]	Cross-section	Cross section class	Non dimensional slenderness $\bar{\lambda}$	Loading protocol
SP27-1	2700	D139.7x6.3	1	0.75	Cyclic, first cycle in tension
SP27-2	2700	D139.7x6.3	1	0.68	Cyclic, first cycle in compression
SP59-1	5900	D139.7x6.3	1	1.64	Cyclic, first cycle in tension
SP59-2	5900	D139.7x6.3	1	1.64	Cyclic, first cycle in compression

All 4 specimens have been tested to cyclic loading according to ECCS (1985). The cyclic tests consisted of four cycles in the elastic range (±0.25Dy, ±0.5Dy, ±0.75Dy and ±1.0Dy), followed by groups of three cycles at amplitudes multiple of 2Dy (3x±2Dy, 3x±4Dy, 3x±6Dy, etc.) The loading was applied quasi-statically, in displacement control. The yield displacement Dy was determined from numerical simulations using mechanical properties of materials obtained from tensile tests.

The SP27-1 specimen buckled out of plane (see Fig. 11) in the first cycle of 2Dy. The washers used to keep the pins into position where fixed to the pin using M6 screws. Due to out of plane buckling, the screws broke, the washers fell off, letting exterior gusset plates bend out of plane. This caused partial loss of contact between the pin and the outer gusset plates, with rapid loss of load bearing capacity of the specimen (see Fig. 15). For the following specimens, new longer pins where fabricated, and stronger washers where used, fixed to the pin through using a thread.

The SP27-2 specimen was modified with respect to the original configuration by welding of two 14x14 mm square sections in the vertical plane, in order to create an unsymmetrical cross-section, forcing in-plane buckling of the brace. This solution proved efficient, buckling taking place as expected, in the plane of the connection (see Fig. 12). Failure took place during the first tension cycle at 6Dy due to fracture of the cross section which experienced local buckling in previous compression cycles (see Fig. 15).

The SP59-1 specimen buckled in the plane of the connection, failure taking place at significant plastic deformations – 16Dy (see Fig. 15). Failure was caused by fracture in tension due to progressive local buckling of the brace in compression (see Fig. 13). The SP59-2 specimen experienced similar level of plastic deformations – 16Dy (see Fig. 15). However, it first buckled out of plane. However, starting with the 4Dy cycles, the buckling changed progressively to in-plane one, failure taking place similar to the previous specimen (see Fig. 14).

Figure 11. Failure mode of the SP27-1 specimen.

Figure 12. Failure mode of the SP27-2 specimen.

Figure 13. Failure mode of the SP59-1 specimen.

Figure 14. Failure mode of the SP59-1 specimen.

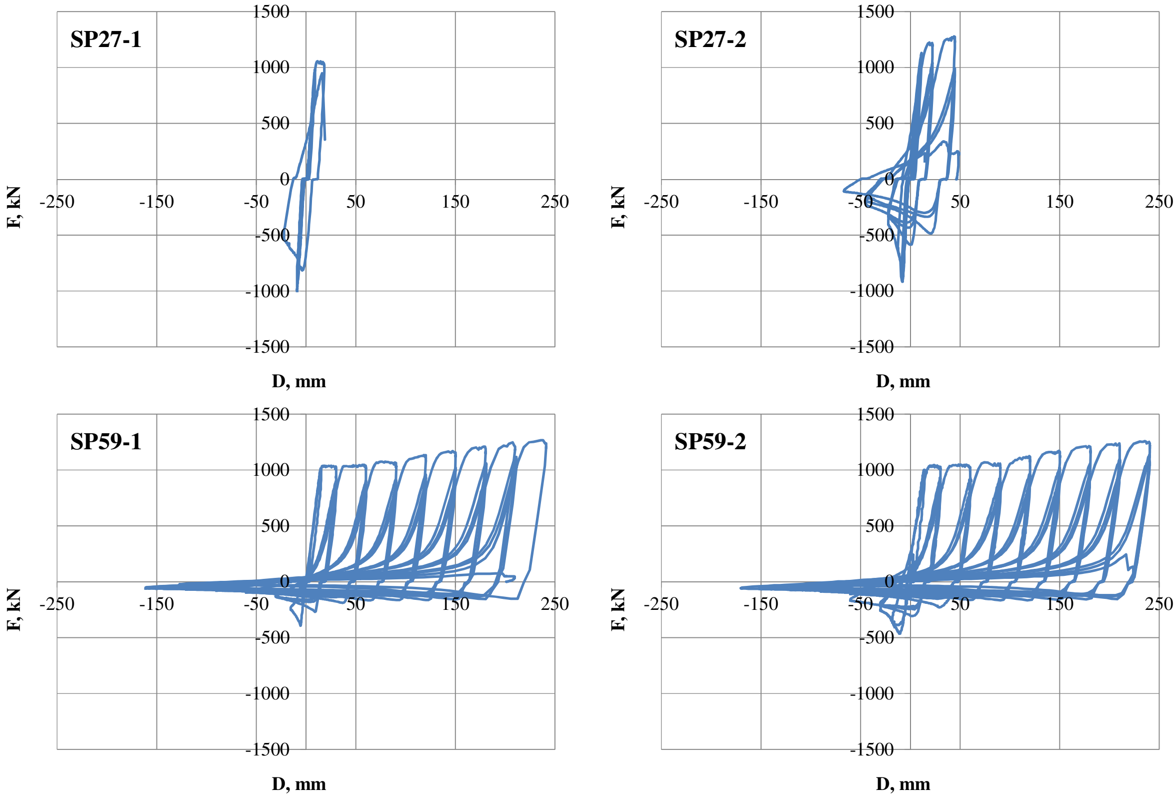


Figure 15. Force – deformation curves of the experimental specimens.

5. CONCLUSIONS

Numerical simulations and experimental testing were performed in order to validate the design of pinned brace for a seismic resistant multi-storey building under design. Based on finite element numerical simulations, a more compact solution was proposed and adopted, using high-strength steel components.

Due to the tubular shape of the cross-section, the brace assembly was shown to be sensitive to out-of plane buckling, leading to failure of the connection in a brittle way. Slender braces are less prone to out of plane buckling. Firmly fixing the washers to the pin also helps preventing brittle failure of the connection, even when buckling takes place out of the plane of the connection. In order to prevent out of plane brace buckling it is suggested using unsymmetrical cross-sections: rectangular, elliptical or wide-flange.

Future work will address study of influence of imperfections on the failure mode of the pinned braces.

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