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PERFORMANCE EVALUATION OF CHEVRON BRACED FRAME AND TADAS DAMPER ON SEISMIC RESPONSE OF STEEL MRFs

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Abstract

The aim of this study is to evaluate the feasibility of seismically strengthening existing steel frames. Through computational analysis of the existing bare frame, two methods of seismic strengthening are proposed. The expected behaviour of each of the three tested steel frames was determined through an initial iterative calculation using numerical models. The dimensions for the two types of strengthening were established based on numerical analysis of the bare frame: one utilizing a specialized inverted V-bracing (Chevron) system, and the other utilizing a dissipative TADAS connection. Following the design of the strengthening, three frames were subjected to static reversed cyclic displacement control tests up to failure, according to FEMA 461. The experimental testing of the bare frame (BF) and TADAS frame (TF) was halted due to the emergence of significant global out-of-plane instability, and testing of the Chevron frame (CF) was discontinued following a brace tensile failure. The ductility of the Chevron frame (CF) is found to be 0.6 times lower, while that of the TADAS frame (TF) is 1.4 times higher in comparison to the bare frame (BF). The initial stiffness of the system is 5 times higher in the CF and 2 times higher in the TF than that of the BF. The cyclic responses of the specimens exhibit a symmetrical behaviour. The TADAS frame dissipates 4 times more energy at the point of failure (brace fracture vs out-of-plane instability) than the CF. Careful design of the braces and plates of the TADAS element is necessary to maintain the plasticization hierarchy.

Keywords: steel frames, seismic strengthening, moment-resisting frame (MRF), TADAS dissipative element, cyclic tests

1. Introduction

The primary objectives of earthquake-resistant design for structures include preventing collapse or severe damage during infrequent but destructive earthquakes, minimizing damage to the supporting structure, and reducing structural damage during occasional moderate earthquakes, and protecting non-structural elements during frequent weak earthquakes. Thus, the acceptable level of damage and the cost of repairs are crucial performance criteria for evaluating the seismic resistance of structures. However, designing structures that meet these objectives while also balancing structural capacity and seismic requirements can be challenging.

Steel is an ideal material for seismic design due to its high strength, ductility, and ability to dissipate energy through yielding and large plastic deformations. It also has a low specific weight and relatively high fracture toughness. To take full advantage of the benefits that steel offers in seismic design, certain conditions must be met:

- The structural system must be designed to ensure inelastic behaviour throughout the system, not just in individual elements, to prevent buckling under cyclic loading.
- Adequate lateral restraints must be provided to prevent lateral buckling.
- Elements with a compact cross-section must be used to prevent local buckling.

Overall, steel's combination of strength, ductility, and low specific weight make it an ideal material for seismic design, but the system must be designed to take full advantage of steel's properties. Two methods for seismically reinforcing steel structures are: a) enhancing the load-carrying capacity while preserving ductility, b) reducing the cross-sectional dimensions of the elements.

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2. Relevant strengthening methods

The seismic safety of steel structures can be improved through the identification and strengthening of the structure's vulnerable points. The presence of substantial constant gravity loads can significantly increase the seismic demands placed on the structure. Thus, it is advisable to reduce the existing constant load and subsequently reinforce the structure's horizontal load-bearing system using appropriate techniques. The use of steel for seismic strengthening is cost-effective and efficient due to the following factors:

- Steel structures are particularly well-suited for performance-based design (PBD)
- Steel elements exhibit ductile behaviour even after reaching the yield point, thus effectively dissipating a significant amount of energy before failure.
- Steel elements have a high strength-to-weight ratio, which results in lower seismic forces acting on the structure.

Concentrically braced frames (CBF) demonstrate superior resistance to horizontal forces and displacement, primarily through the utilization of the longitudinal strength and stiffness of the braces. These frames are engineered such that the centroidal axes of the columns, beams, and braces align, thereby minimizing bending effects. CBFs are designed to exhibit low levels of inelastic deformation and to withstand larger seismic forces to compensate for their lack of ductility. They are well-suited for use in smaller structures as the design calculations are relatively simple compared to other types of braced frames. Additionally, CBFs are more cost-effective than moment-resisting frames (MRF) due to their lower material requirements. However, they may be less suitable for larger structures and structures subject to high seismic demands [1].

Special concentrically braced frames (SCBF) have distinct requirements in comparison to conventional frames, which concentrates the inelastic behaviour of the structure on the braces and enhances the ductility of the braces and their connections. These requirements enable greater energy dissipation and ductility, resulting in the ability to design these frames for lower loads than regular braced frames. The increased energy dissipation capacity and ductility make them particularly suitable for use in areas with higher seismic demands. Figure 1 illustrates typical configurations of concentrically braced steel frames.

Other frequent strengthening techniques include eccentrically braced frames and buckling-restrained braced frames (BRBF), which are not the focus of this research.

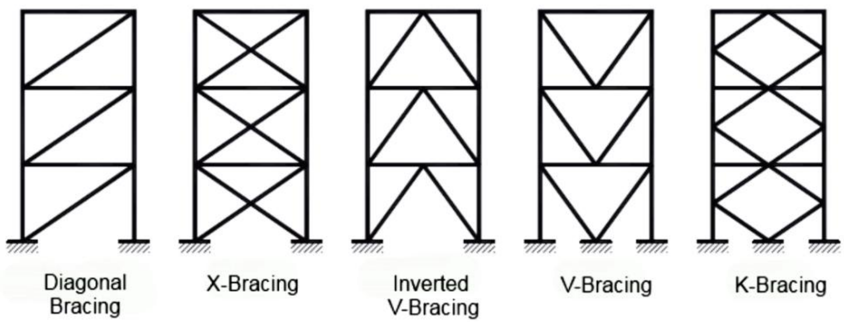

Fig. 1 – Typical configurations of centric steel braced frames [2]

Numerous studies have been conducted to enhance the seismic performance of Chevron braced frames (Inverted V-Bracing). Researchers have specifically examined the use of novel technologies such as dampers, and each system has its own advantages and disadvantages. The idea of using dampers in bracing systems was first proposed by [3] who developed the ADAS (Added Damping and Stiffness) system and [4] who created TADAS (Triangular Plate Added Damping and Stiffness), conducted experimental tests and theoretical studies.

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The ADAS and TADAS steel plate devices (Figure 2) are a series of steel plates intended for use in frame structures. They are activated during relative story displacement, causing the top of the plate to move horizontally relative to the bottom of the plate. The yielding of the steel plates enables the ADAS/TADAS device to dissipate a significant amount of energy during an earthquake. The energy dissipation through yielding ADAS/TADAS devices has several benefits:

- the energy dissipation is concentrated in designated areas,
- the energy dissipation demands of other structural elements are reduced,
- the yielding of the ADAS/TADAS device does not compromise the capacity of the vertical load-bearing system supporting the gravity loads, as the device is a component of the horizontal stiffness system and does not significantly affect the vertical stiffness.

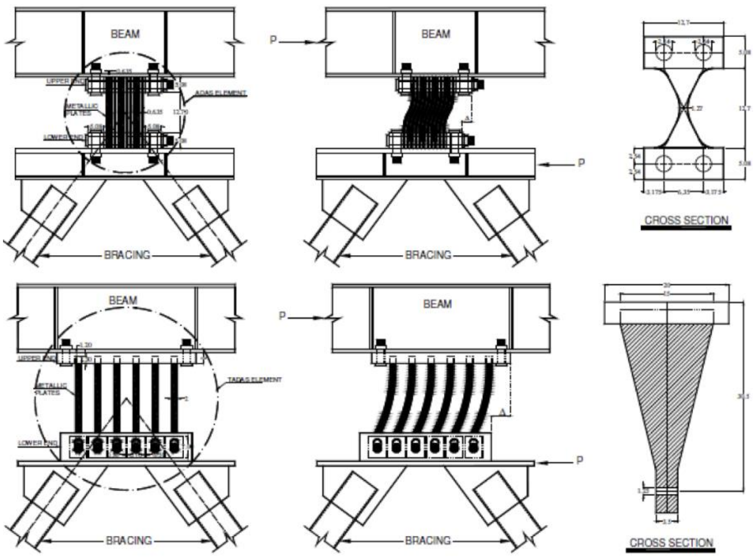

Fig. 2 – The behaviour of ADAS (upper) and TADAS (lower) dampers during an earthquake [3, 4]

3. Geometric and material properties of the frame specimens

The steel frame specimens used in this study consist of HEA 120 columns connected at the top to HEA 120 beam. The beam is equipped with face plates, which serve to increase the contact area over which shear loads are applied. The columns are connected at the bottom by a beam with HEB 220 cross-section (Figure 3). The yield strength and tensile strength are obtained from [5], with an average yield strength of 337 MPa and an average tensile strength of 483 MPa. The modulus of elasticity is 210 GPa. It is worth noting that the frames utilized in this research have already been tested by [5] and as such have minimal imperfections stemming from residual deformation, as the frame specimens barely reached their yield strength. A bare frame is depicted in Figure 3a. The rotational stiffness of the joint was determined numerically to be 2 MNm/rad, which is essential for future numerical analyses.

It was determined to use the Special Concentric Braced Frame (SCBF) in conjunction with the dissipative TADAS device. All steel used for the strengthening is of grade S235. The Chevron-shaped Special Concentric Braced Frame (CSCBF) allows for in-plane or out-of-plane buckling of the diagonal elements. For architectural and safety reasons, a design was chosen in which the diagonals buckle in-plane. The diagonal buckling is ensured by a knife plate with a clear width of $3 \cdot t_p$, where t_p is a knife plate thickness of 8 mm. The design of all details was carried out iteratively [1, 6]. Figures 3b and 4 illustrates the adopted dimensions, which ensure over 85% utilization of the element and the compliant hierarchy of diagonal brace elements (HSS 50×50×3.2 mm). The same brace cross-section is employed when the bare frame is strengthened with a TADAS dissipation device. In this instance, the utilization of the diagonal braces is slightly lower as the buckling length is smaller. The calculation was performed according to [4], and the dimensions can be seen in Figures 3c and 6.

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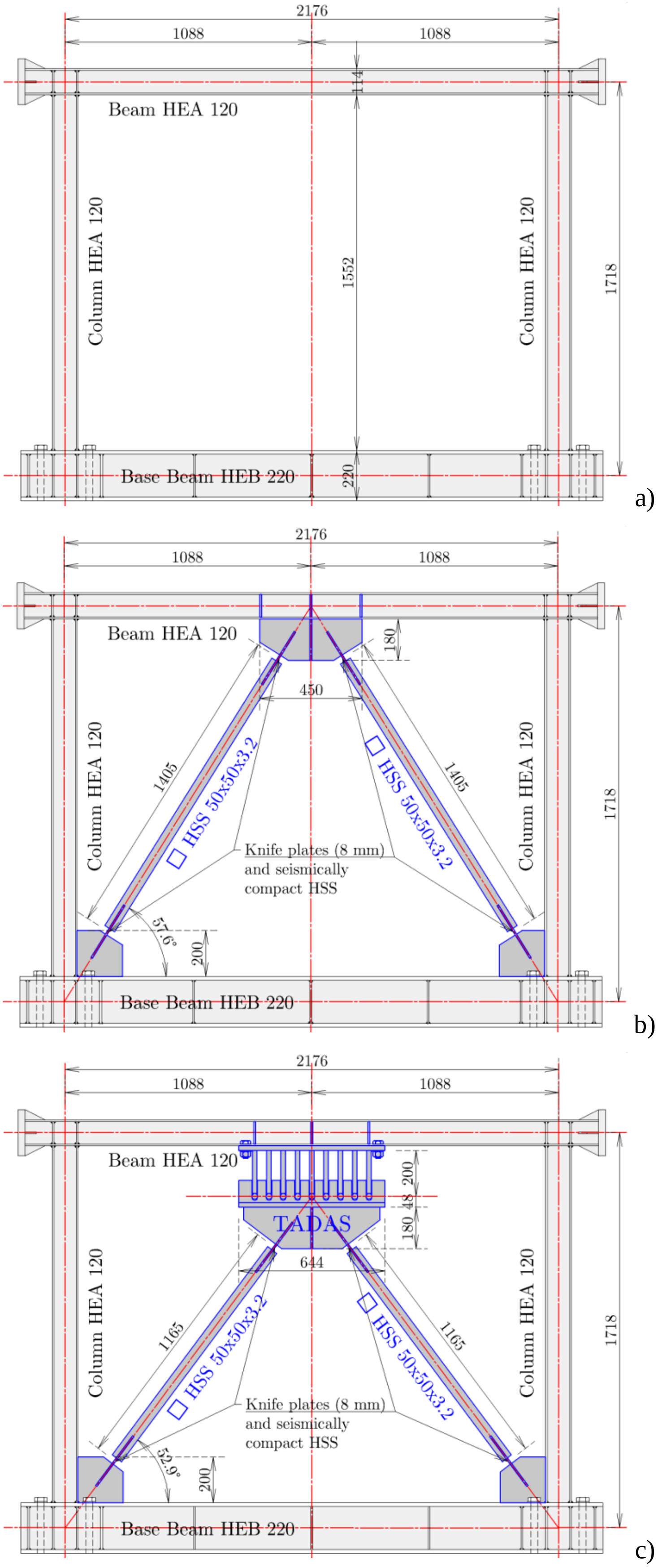

Fig. 3 - Geometries of test steel frames: a) Bare frame, b) Inverted V-braced/Chevron frame, c) TADAS frame

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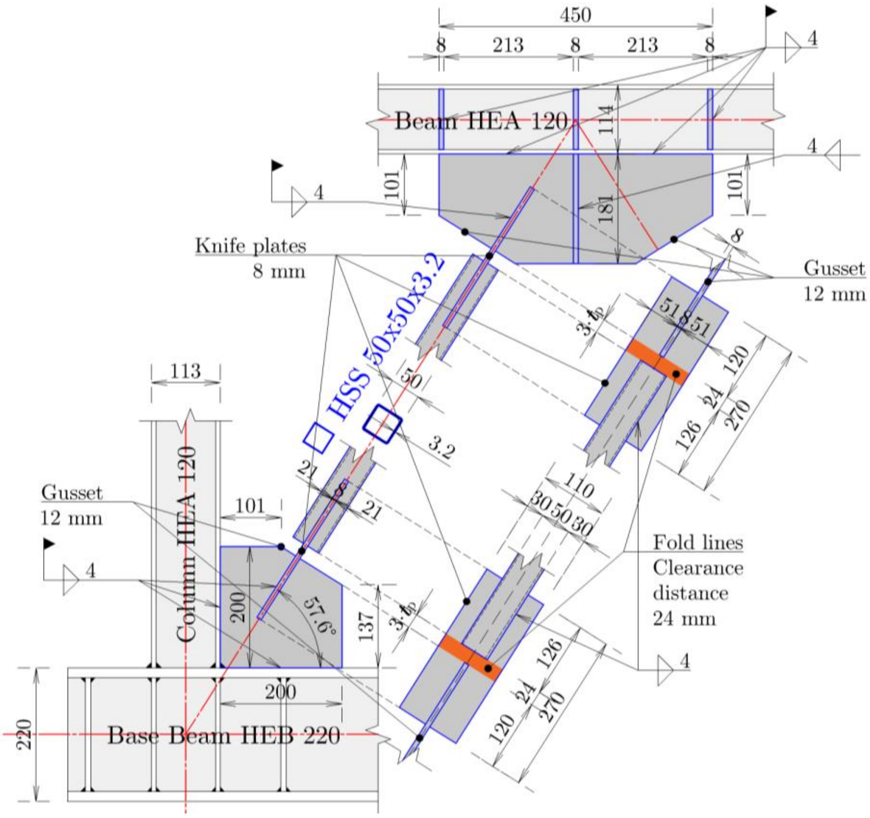

Fig. 4 - Details of diagonal element connections, gusset plates, knife plates, clearance distances and welds

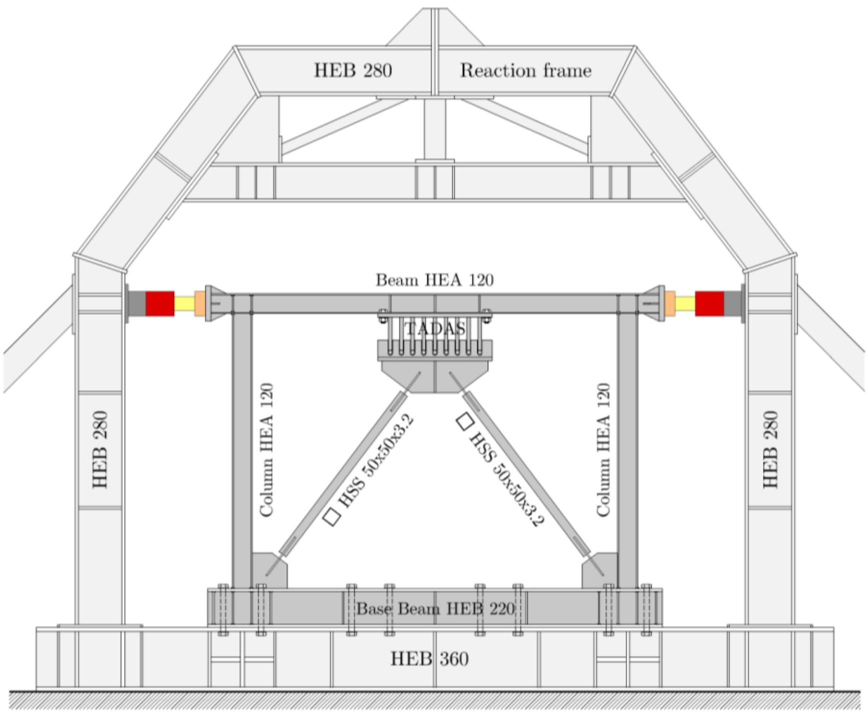

Fig. 5 – Steel frames within reaction frame for cyclic testing

TADAS was designed and ultimately consisted of 9 plates of class S235, a height of 200 mm, a base width of 80 mm and a thickness of 20 mm (Figure 6). Before the static cyclic tests, the first three natural frequencies were determined and summarized in Table 1.

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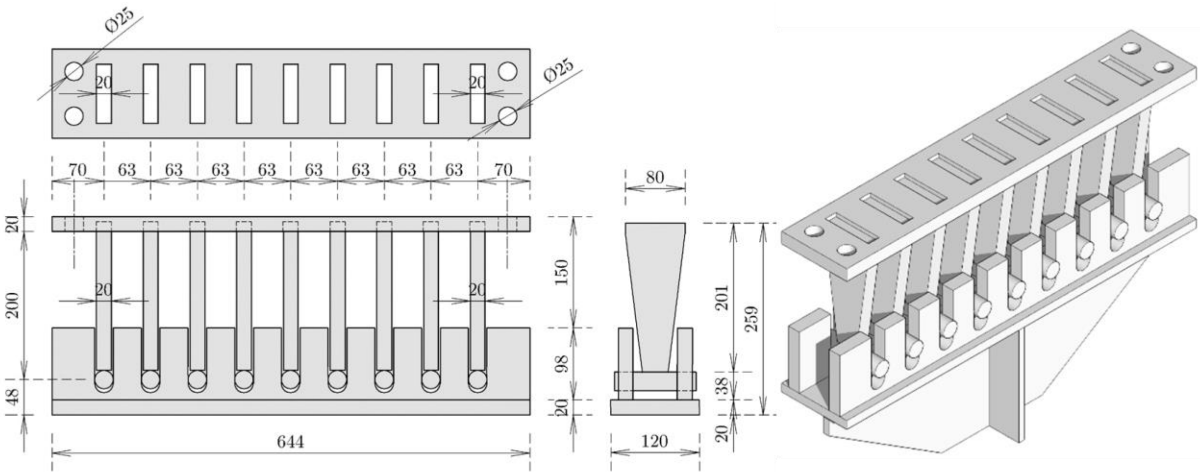

Fig. 6 – Geometric details of the TADAS dissipative element

Table 1. Natural frequency values for all tested frames

Eigenmode shape	Natural frequencies [Hz]		
	Bare frame	Chevron (Inverted V-braced) frame	TADAS frame
#1 / Out-of-plane	8.36	9.40	7.20
#2 / Torsion	10.80	12.45	12.51
#3 / In-plane	30.09	86.30	46.88

4. Global response of steel frames

The static cyclic tests were conducted in accordance with the protocol of FEMA 461 [7], using a total of 13 cycles to target displacement. The frames were loaded in the horizontal direction only, without any constant gravity loading. The maximum lateral load capacity for the Chevron frame was twice as high (up to 200 kN) and three times as high for the TADAS frame (up to 300 kN) compared to the bare moment-resisting steel frame (up to 100 kN) as illustrated in Figure 8. Testing was interrupted for the bare and TADAS frames after substantial out-of-plane instability occurred, and for the Chevron frame after a diagonal tensile failure (Figure 7). In the case of the TADAS frame, buckling of the compression diagonals did not occur, which would have been anticipated with larger displacements. This is because the dissipative TADAS element, consisting of 9 plates, hardens during the test, resulting in an emphasized isotropic hardening.

a)

b)

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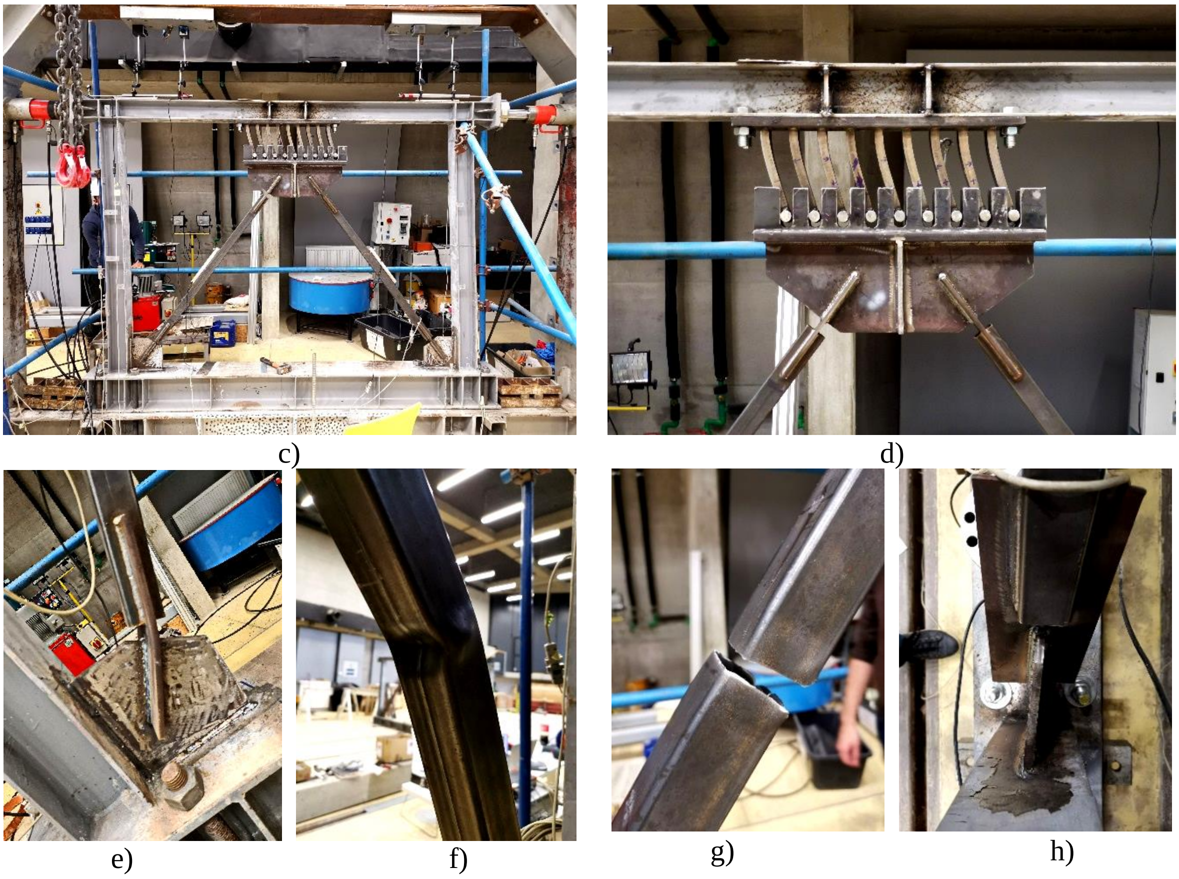

Fig. 7 - Photos of steel frame specimens during static tests, a) Bare frame, b) Chevron frame (Inverted V-braced frame), c) & d) TADAS frame, e) rotation of knife plate on Chevron frame due to buckling of compression diagonals, f) & g) before and after fracture of tension diagonals in Chevron frame, h) out-of-plane instability of frame (torsion), whereupon tests on TADAS frame were stopped.

Figure 9 presents the hysteresis envelopes in conjunction with the corresponding secant stiffnesses of individual specimens. The envelopes are generated as an average of the positive and negative load directions to consider imperfections in the test specimens and boundary conditions.

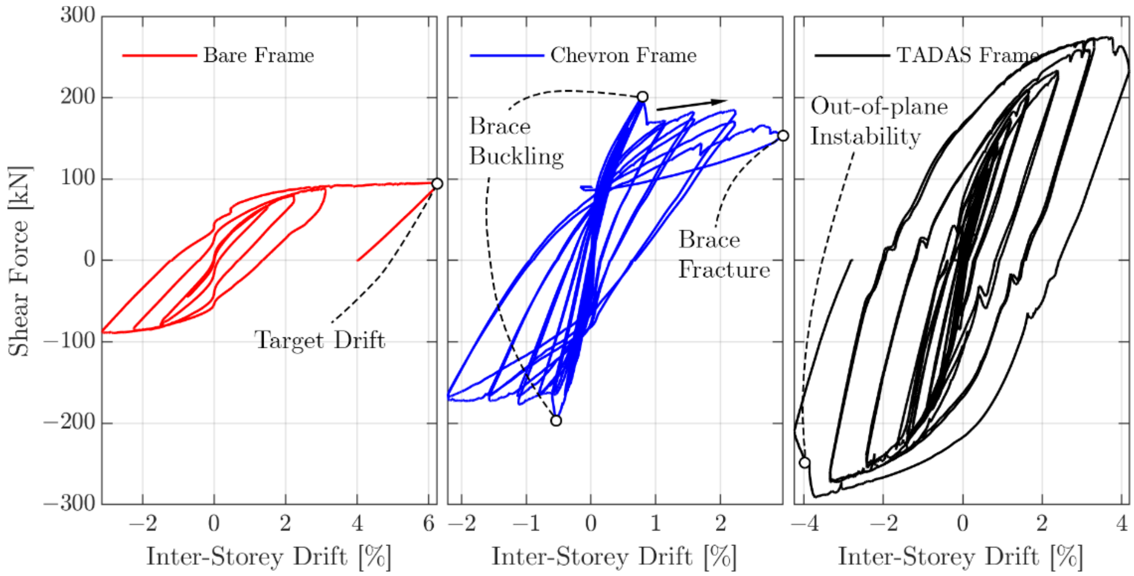

Fig. 8 - Global hysteresis responses of all steel frames

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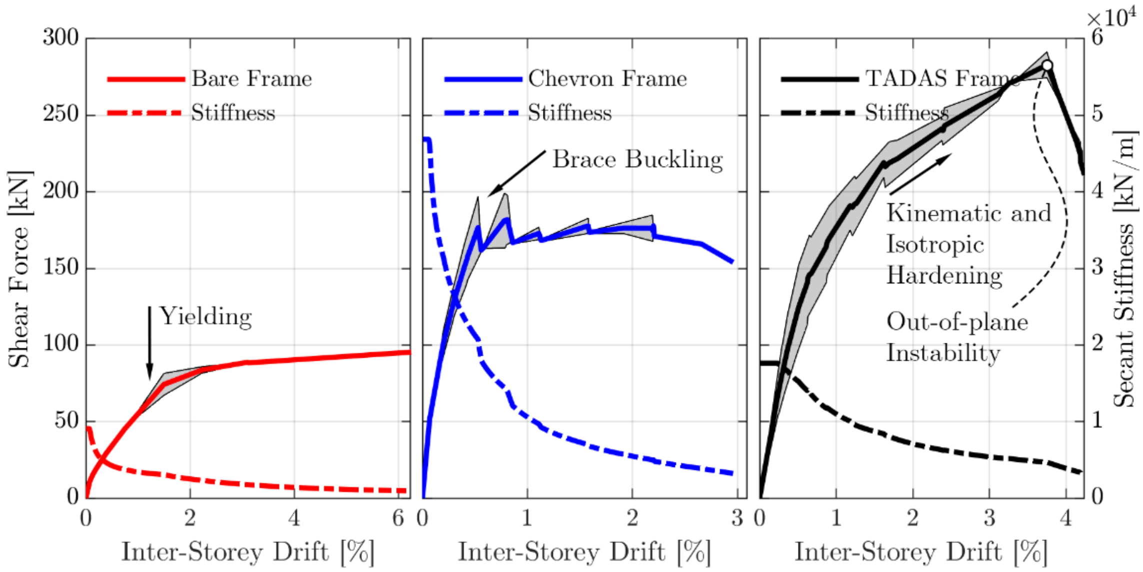

Fig. 9 - Hysteresis envelopes and associated secant stiffnesses for all steel frames

The experimental testing of the bare frame (BF) and TADAS frame (TF) was prematurely terminated because of significant global out-of-plane instability. Similarly, testing of the Chevron frame (CF) was discontinued due to a brace tensile failure. No buckling of the compression diagonals was observed in the TF. The TF exhibited a greater emphasis on isotropic hardening. The ductility of the CF was found to be 0.6 times lower, while that of the TF was 1.4 times higher in comparison to the BF. The initial stiffness of the system was determined to be 5 times higher in the CF and 2 times higher in the TF, in comparison to the BF. The cyclic responses of the specimens displayed symmetrical behaviour. The cumulative energies are illustrated in Figure 11, up to the largest common cumulative displacement.

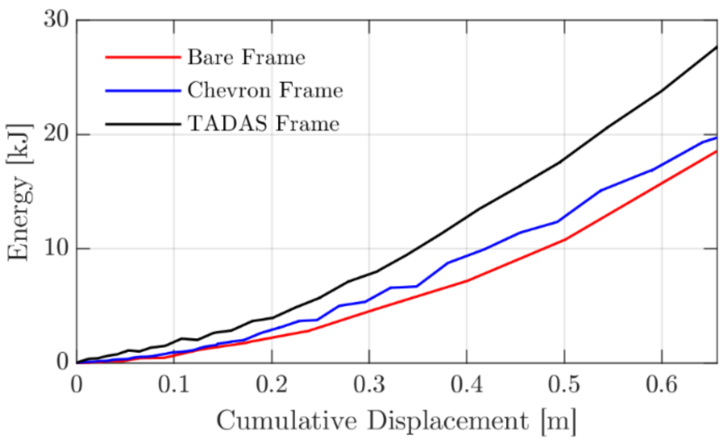

Fig. 11 – Cumulative hysteretic energies up to the largest common cumulative displacement

4. Conclusions

The utilization of strengthening techniques can significantly contribute to an improved response of steel frame structures in seismic design scenarios. The strengthening measures can be applied during the design stage of the structure or after it has been constructed. During design, the incorporation of strengthening measures can decrease the dimensions of the column cross-section, resulting in a more efficient design. By strengthening an existing structure, an increase in horizontal stiffness can be achieved.

Both types of strengthening resulted in higher load-bearing capacity compared to the un-reinforced frame. The diagonally braced frame (Chevron frame) achieved twice the lateral load-bearing capacity

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compared to the bare frame, while the TADAS frame achieved almost three times the load-bearing capacity compared to the un-reinforced frame. A frame with concentric bracing could only achieve just under half the displacement compared to a bare frame. The frame with the dissipative TADAS connection achieved 32% greater displacement than the frame stiffened with concentric bracing. The TADAS frame is more ductile than the Chevron frame and has a higher load-bearing capacity, which is a desirable behaviour. The behaviour of a bare frame can be predicted well. Damage occurs at the expected locations, namely at the base of the columns. It is assumed that the bare frame would have made larger displacements if there had not been a loss of out-of-plane stability.

It was expected that the TADAS frame would withstand a greater load than a Chevron frame, which was the case. The advantage of this type of strengthening is that it has retained the best behavioural characteristics of the other two types of strengthening, i.e., the advantage of higher load-bearing capacity with sufficient ductility.

Experimental testing of the bare frame (BF) and TADAS frame (TF) was prematurely terminated due to the emergence of significant global out-of-plane instability. Testing of the Chevron frame (CF) was similarly discontinued as a result of brace tensile failure. Analysis revealed that the ductility of the CF was found to be 0.6 times lower, while that of the TF was 1.4 times higher, in comparison to the BF. The initial stiffness of the system was determined to be 5 times higher in the CF and 2 times higher in the TF, in comparison to the BF. The cyclic responses of the specimens displayed symmetrical behaviour. The TF was observed to dissipate 4 times more energy at the point of failure (brace fracture vs out-of-plane instability) than the CF. It is thus important to carefully design the braces and plates of the TADAS element in order to maintain the plasticization hierarchy.

References

[1] AISC, American Institute of Steel Construction (2018) Seismic Design Manual, Third Edition, ISBN: 978-1-56424-035-4.
[2] Ülker, M., Işik, E., Ülker, M. (2017) The Effect of Centric Steel Braced Frames with High Ductility Level on the Performance of Steel Structures, *In proceedings: International Conference on Advances and Innovations in Engineering* (ICAIE)
[3] Whittakar, A., Bertero, V., Alonso, J., Thompson, C. (1989) Earthquake Simulator Testing of Steel Plate Added Damping and Stiffness Elements. *Report No. UCB/EERC-89/02*. Earthquake Eng. Res. Center Univ. California, Berkely, URL: https://nehrpsearch.nist.gov/static/files/NSF/PB92192988.pdf
[4] Tsai, K., Chen, H., Hong, C., Su, Y. (1993) Design of Steel Triangular Plate Energy Absorbers for Seismic-Resistant Construction. *Earthq. Spectra*; 9(3): 505-28., DOI: https://doi.org/10.1193/1.1585727
[5] Radić, I. (2012) Ponašanje čeličnih okvirnih građevina sa zidanim ispunom pri djelovanju potresa, PhD Thesis, University of Osijek, Croatia, URL: https://www.bib.irb.hr/608906
[6] Landolfo, R., Mazzolani, F., Dubina, D., Simões da Silva, L., D'Aniello, M. (2017). Design of Steel Structures for Buildings in Seismic Areas: Eurocode 8: Design of structures for earthquake resistance. Part 1-1 – General rules, seismic actions and rules for buildings, Print ISBN: 9783433030103, Online ISBN: 9783433609194, DOI: https://doi.org/10.1002/9783433609194
[7] FEMA 461 (2007), Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components, Applied Technology Council, Prepared for Federal Emergency Management Agency, URL: https://www.atcouncil.org/pdfs/FEMA461.pdf