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EXPERIMENTAL BEHAVIOUR OF REDUCED-SECTION THIN WALLED DIAGONALS

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Abstract

This paper presents the experimental behaviour of dissipative thin-walled reduced-section diagonals. These elements are designed to be the dissipative elements of rack-supported warehouse and are organised in an X-tension-only layout. The cross section of these diagonals has been locally reduced to allow dissipation through yielding and for the diagonal-to-column connection to be over-resistant, according to the capacity rules for the adopted structural scheme. After a numerical study around the design of the dissipative element, the behaviour has been validated through an extensive experimental campaign, where tensile and compression monotonic tests are performed, as well as cyclic ones on profiles with different layouts for the reduced sections.

Keywords: Dissipative Rack Supported Warehouses, Cold-formed elements, Dissipative reduced-section diagonals, Experimental validation, Dynamic behaviour, Structural Performance.

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1 INTRODUCTION, RESEARCH OBJECTIVES AND METHODOLOGY

Rack Supported Warehouses (RSWs) are steel structures used for storing palletised goods, where the racks serve both as storage and as the main structural system. Despite this dual role, no dedicated design rules exist for RSWs. As a result, designers still rely on standards for simple racks (EN15512 and EN16681 [1, 2]) and Eurocodes, which are not entirely suited to RSWs due to their unique structural characteristics [3–5]. Notably, RSWs maintain the same assembly and technological solutions as simple racks [6], always adopting cold-formed elements. This lack of tailored design methods poses significant safety risks, particularly in seismic zones, where local failures have resulted in operational disruptions and substantial financial losses. From a serviceability perspective, even local damage can be as critical as global collapse due to the impact on warehouse functionality.

RSWs structural vulnerabilities were highlighted by several Authors [7, 8], who evaluated the seismic vulnerability of some case studies designed according to current approaches. The seismic vulnerability was assessed through non-linear time-history analyses, and safety checks were performed on all structural components. The most vulnerable components resulted in the base and diagonal-to-upright connections (Figure 1). Base connections typically consist of welding the base of the upright on a steel plate to be fixed to the concrete slab with post-installed bonded anchors. Failures here are brittle, caused by combined shear and tension forces. Diagonal-to-upright connections' leading mechanism is bearing (diagonal side) mainly due to the very low thickness of these elements, leading to ovalisation and potential loosening. While not inherently brittle, these should only be accepted under limited dissipation expectations, with other fragile failures strictly avoided. To conclude, if dissipation is expected, available post-elastic mechanisms are inadequate, highlighting the urgent need for a dedicated design methodology for seismic-resistant RSWs.

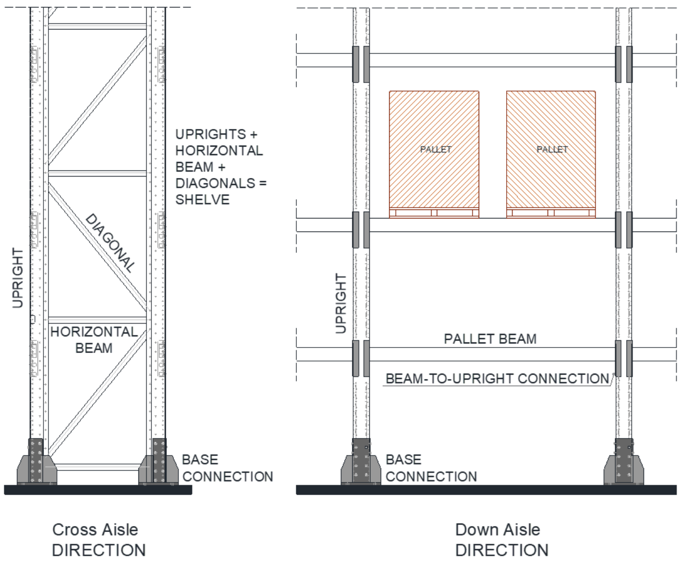


Figure 1: Main components of racking systems.

To develop a dedicated design method for dissipative RSWs, thinking also of nowadays possible solutions [9–11], two methods have been developed: the Plastic Ovalisation Strategy and the Over-resistant Connection Strategy (OCS). The former is based on the possibility to allow limited dissipation in correspondence of the diagonal-to-upright connection by overstepping bearing resistance and allow some plasic ovalisation. This method has been numerically [12] and experimentally [13] validated, and is very much appreciated by rack designers and producers for its ease of design and continuity in the techniques and procedures used to realise these elements. On the other hand, ductility and dissipation capabilities are limited, as high deformations in the connection may result in largely loose structures. As an alternative, the OCS strategy enables a dissipative behaviour, concentrating energy dissipation in the diagonal bracings through yielding under tensile axial force, while all other components are designed to remain elastic and over-resistant with respect to the depicted weak mechanism.

The strategy is based on Eurocode 8 guidelines for X-shaped, tension-only bracing systems, with modifications introduced to suit the structural specifics of RSWs. In particular, since diagonal-to-upright connections are complex to be over-resistant to the yielding of the brace due to the low thickness of the diagonals, local reduction of the diagonal's cross-section is necessary [14]. The local section reduction ensures that the diagonals yield before the connections fail, as required by capacity design principles. On the other hand, the introduction of the spotted section reductions increases the local and global slenderness of the profile, which may negatively affect their performance in compression and under cyclic loads. For this reason, the design of the reduced spots shall be carefully performed, considering global ductility levels to be achieved – directly related to local diagonal ductility - and local and global slenderness to be controlled.

A comprehensive explanation of the development and numerical validation of the approach is provided in [15], demonstrating its potential and benefits. Still, the actual behaviour of the reduced section diagonals needs to be assessed via experimental tests to properly analyse the influence of the layout of the reduced sections on the performance of the braces.

This paper presents the experimental behaviour of a cold-formed brace with four different layouts for the reduced section spots. The layouts aim for similar levels of ductility, but with different lengths, numbers, and distributions of the reduced-section spots. The elements are first tested under monotonic tensile and compression loads and then under cyclic loads.

2 DESIGN OF THE SECTION REDUCTIONS

Following the design procedure shown in [15], four possible layouts have been investigated for the selected C cold-formed diagonal, as represented in Table 1.

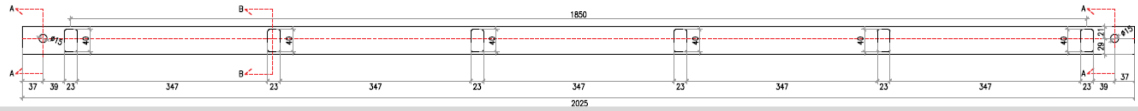
The diagonal has been extracted from a case study structure designed following the whole approach and for a medium-high seismicity zone (pick ground acceleration equal to 0,3g). A thickness of 2 mm characterises the element. To accommodate the over-resistance of the diagonal-to-upright connection, the full section has been reduced by 72%, and for the connection, a 1 M14 bolt of class 8.8 has been adopted.

A rectangular shape has been used for the reduced sections, which the previous study [15] found to limit local deformation in compression for a more global buckling mode. Then, different lengths and quantities for the reduced spots have been proposed for similar levels of ductility and similar buckling strength, always ensuring that the buckling mode remains mainly global.

Layout	**L1**	**L2**	**L3**	**L4**
Total length of the reduced sections [mm]	138	114	152	124
Distribution of reduced sections	diffused	diffused	diffused	diffused
Number of reduced sections	6	6	8	4
Length of each re-	23	19	19	31

duced part [mm]				

L1



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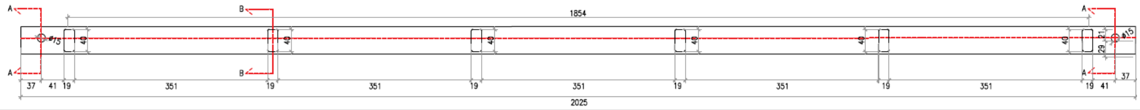

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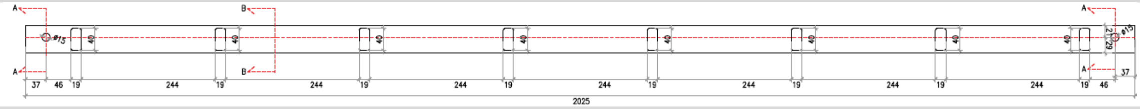
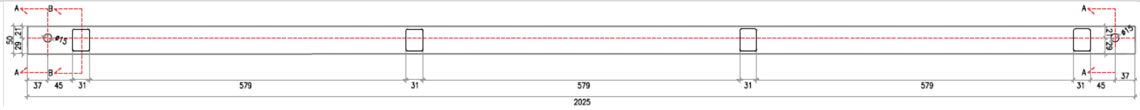


L4



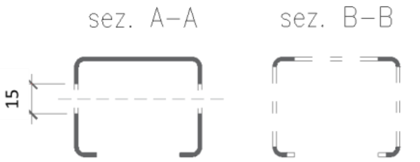


Table 1: Layout of the reduced-section elements.

3 EXPERIMENTAL CAMPAIGN

The objective of the tests is to compare the structural performance of different layout configurations by evaluating several key aspects: tensile resistance and ductility, buckling mode, slenderness of the diagonal, and degradation in resistance or stiffness under cyclic loading, if any. Each diagonal is tested in its actual structural configuration, meaning it maintains the same geometry as assembled with the upright. The test assembly consists of the diagonal connected to two upright segments, allowing verification of compliance with the OCS design principles. Special attention is given to confirm that the expected behaviour occurs — specifically, that no damage is observed in the upright-to-diagonal connection. This setup helps validate whether the safety coefficient used for designing over-resistant components has been appropriately calibrated. The experimental setup is illustrated in (Figure 2), and each element is tested under monotonic tensile and compression loads and then under cyclic load. The loading protocol for the latter follows the ECCS recommendation titled “Recommended testing procedure for assessing the behaviour of structural steel elements under cyclic loads” [16].

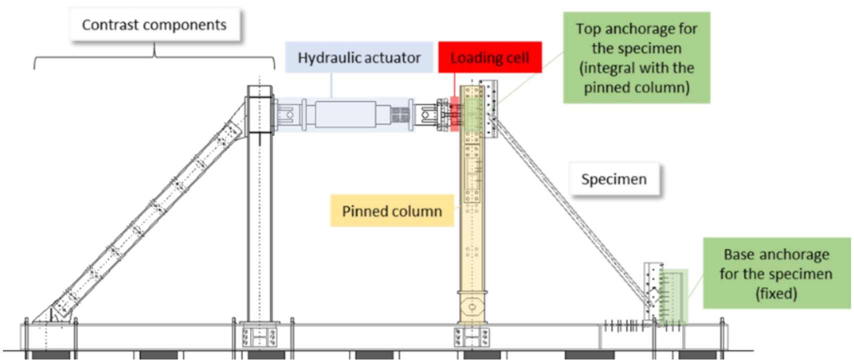


Figure 2: Test set up for OCS diagonals tests.

Under monotonic tensile loading, the observed failure mode for all the layouts involves yielding followed by tearing of the brace at the reduced cross-section located nearest to the connection (Figure 4a). No signs of damage were found at the connection, confirming that the over-resistance provided following the design rules seems sufficient to avoid preliminary failure in connection. Looking at force/displacement curves (Figure 3), all the layouts allow to reach similar levels of ductility, as foreseen at the design phase.

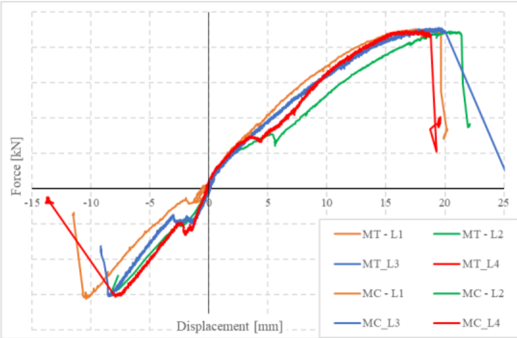


Figure 3: Monotonic tensile and compression behaviour of the tested elements.

(a) (b)

Figure 4: Failure of the elements under monotonic (a) tensile and (b) compression load.

In the case of monotonic compressive loading, global buckling anticipates the local buckling of the reduced-section portions in the first three layouts, which are characterised by shorter reduced spots. When the deflection of the diagonal due to global buckling is high, compression/bending interaction induces local buckling into the reduced spots. Layout L4 is characterised by the lowest number of reduced spots, but by the larger ones. This induces a mixed local/global buckling mode (right from the very first phase of instability), with the relevance of local buckling of the reduced spots.

The cyclic behaviour is primarily characterised by global buckling of the brace, followed by local buckling in the area with reduced cross-sections, and ultimately by fracture occurring in the locally buckled reduced zone (Figure 6). In the case of L4, buckling mode is global/local mixed from the very beginning. Importantly, yielding of the reduced spots can be observed, with no damage occurring in the connections. An optimal correlation with monotonic tests can be observed (Figure 5), with a slight degradation of stiffness in tension due to the early buckling of the element. Failure under tension load occurs both close to the end sections or in the mid-length reduced-sections deformed due to local buckling (little cracks may appear after a few cycles).

From a failure mode perspective, the Over-resistant Connection Strategy results to effectively concentrate damage within the brace, successfully protecting the uprights and the connection area. Although achieving over-resistance may require a significant reduction of the diagonal’s cross-section, the L1 to L3 layouts allow global buckling to precede local buckling, while L4 proves that too long reduced sections may anticipate local buckling, negatively affecting the performance of the element. In general, when buckling does occur in the reduced section, it significantly influences the overall behaviour of the brace, as failure often initiates in this region. Limiting the length of the reduced spots can slow down this effect, as local buckling of the reduced spots starts at high deflection of the beam due to global instability.

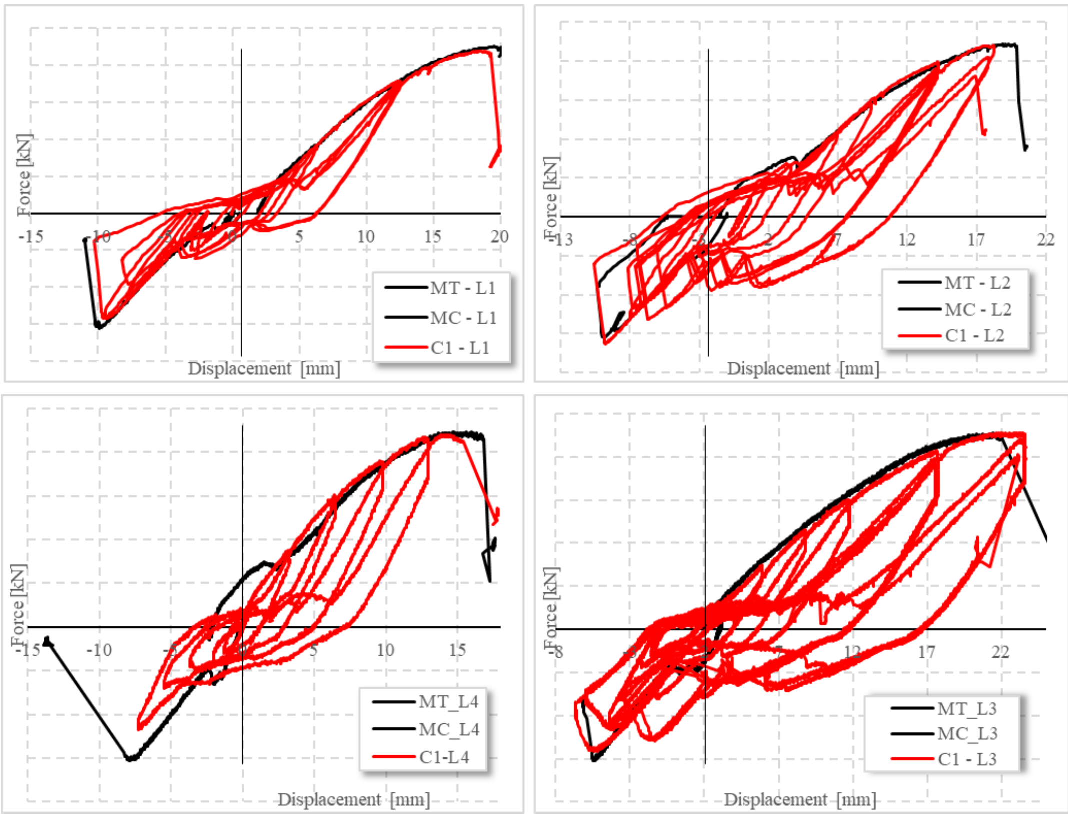


Figure 5: Cyclic behaviour of the tested elements.

Figure 6: Failure of the elements under cyclic load.

Furthermore, repeated load-unload cycles may cause micro-cracks in the locally buckled zone, which can lead to fracture under subsequent tensile loading. Despite these localised effects, minimal global degradation in stiffness or strength was observed throughout the cyclic tests. Finally, in the monotonic tensile tests, failure always occurs in the reduced section spot closest to the connection and in a non-symmetric way (despite the section has been reduced to maintain the geometrical barycentre aligned with the one of the gross section, and connection is aligned with this barycentre). This may be caused by the proximity of the first reduced spots to the connection, leading to a missing uniform redistribution of stresses in the limited distance between the connection and the first reduced section. This aspect will be carefully analysed and taken into account in further studies.

4 CONCLUSIONS

This paper shows the experimental behaviour of reduced-section thin walled braces for Rack Supported Warehouses. They have been designed following the early proposed Over-resistant Connection Strategy (OCS) design method, specifically developed for RSWs, which enables energy dissipation to be concentrated in the diagonal braces while ensuring all other components remain over-resistant.

According to the desired behaviour, dissipation shall be confined to the diagonals, and the only way to ensure the typical diagonal-to-upright connections are over-resistant is to reduce the resistance of the diagonals by locally reducing their cross-section. The design of the reduced-section diagonals is initially performed through analytical calculations according to the design methods, followed by numerical simulations to design possible layouts for the reduced spots. The layout of the reduced-section spots indeed have effects on local/global ductility to be reached, and on buckling mode of the diagonal. Global buckling is preferred with respect to local one, since may limit fast cyclic resistance and stiffness degradation and assure good hysteretic behaviour.

Four layouts have been properly designed for a diagonal extracted from a case study structure designed following the OCS procedure, and their structural behaviour has been validated through an extensive experimental campaign. The four layouts have been designed to achieve a similar level of ductility under tensile force, to exhibit a global buckling mode under compression force, and to ensure the over-resistance of the connection with respect to the yielding of the brace.

Test results confirm that the OCS approach effectively localises damage in the braces and prevents failure in the uprights and connection zones. Even with significant section reductions, the diagonals performed well under compression, with global buckling occurring before local instability, as intended. Only in the case of longer reduced spots (L4), the buckling mode is a mixed global/local one. Under cyclic loading, local buckling in the reduced sections can lead to crack formation and tensile failure due to repeated stress reversals. However, optimising the balance between connection strength and section reduction—by reducing the extent of section cuts—could improve cyclic performance and prevent local buckling entirely.

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