STEEL PALLET RACKS

Experimental characterization of the cross- and down-aisle seismic behaviour

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INTRODUCTION

Prediction of the structural behaviour of storage racks is known as a difficult task because affected by the particular geometry of their structural components, i.e. members made by high slenderness thin-walled elements hence prone to global, local and, for the uprights, distortional buckling problems. Moreover specific modelling and design rules are required for these non-traditional steel structures, especially for the beam-to-upright and base-plate joints in the down-aisle direction that exhibit a strongly non linear behaviour. In the cross-aisle direction, stability is ensured by frames consisting of two uprights connected by bracing members as shown in *Fig. 1*.

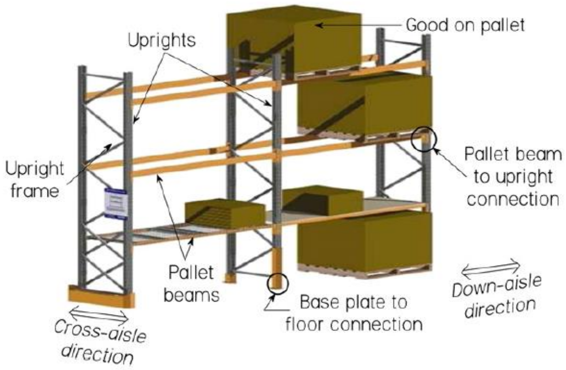

Fig. 1. Typical storage rack configuration.

Design is even more complicated for racks installed in seismic zones, where they must be able to withstand horizontal and vertical dynamic. Whilst the basic technical description of an earthquake is obviously the same for all types of structures, it is of great importance to define whether or not it is possible to apply the "general design rules" (applicable to ordinary steel structures) to a rack. Furthermore it is necessary to consider how to modify correctly the general principles and technical requirements, in order to take into account the peculiarities of racking and to achieve the requested safety level.

Results presented in this paper are part of a wide research program "Seisracks2 – Storage Racks in Seismic Areas" funded by the European Union, which aims at constituting a scientific background document for the conversion of the Code of Practice FEM 10.2.08 to a European Standard.
The present paper summarizes the current situation of two main aspects of this research: (i) the investigations carried out on the cross-aisle behaviour, with the objective of covering a wide range of configurations and to investigate their consequences on the transverse stiffness, resistance and deformation capacity of the frame; (ii) the behaviour in down-aisle direction in presence of eccentric vertical bracings with a significant torsional component due to the eccentricity of the bracing system with respect to the centre of mass of the stored goods.
The objectives of the study are to provide an experimental corpus available for proper calibration of numerical models and to define testing procedures suitable for the identification of the main structural parameters easily transferrable into numerical models. These various issues are investigated by means of full scale push-over and cyclic testing.

1 CROSS-AISLE BEHAVIOUR

Independently of any seismic consideration, the European Standard EN 15512 [1] requires testing to evaluate the transverse stiffness per unit length of an upright frame (Fig. 2).

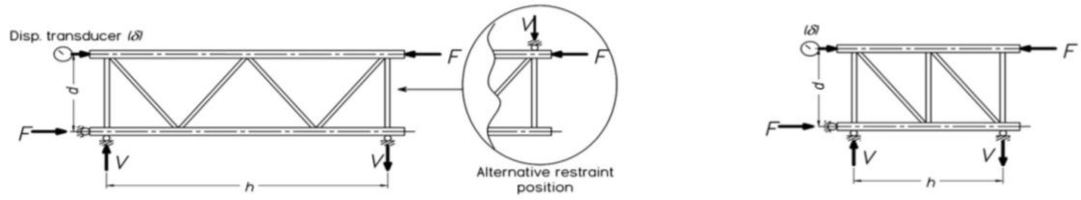

Fig. 2. Upright frame shear stiffness setup in EN 15512 [1].

This test is however characterizing the behaviour under pure shear, while the reality of the earthquake situation implies the combination of a shear loading varying over the height of the frame and combined with a significant overall bending contribution.

The purpose of the alternative test setup proposed in the present study is thus to focus on a more realistic loading procedure: 8 meter high frames are tested transversally with 4 equally distributed load levels, in such a way to have a linear triangular distribution, corresponding to the beam levels of the case-studies configurations, i.e. to levels where the masses are actually present. Vertical side guides prevent out-of-plane instabilities. No direct axial force is applied on the uprights, implying the base connection to be designed appropriately to resist the tension induced by the overall bending of the system, in order to focus on a collapse in the main part of the frame and not in its connections to the floor. Displacement transducers are located as seen on *Fig. 3.b)*.

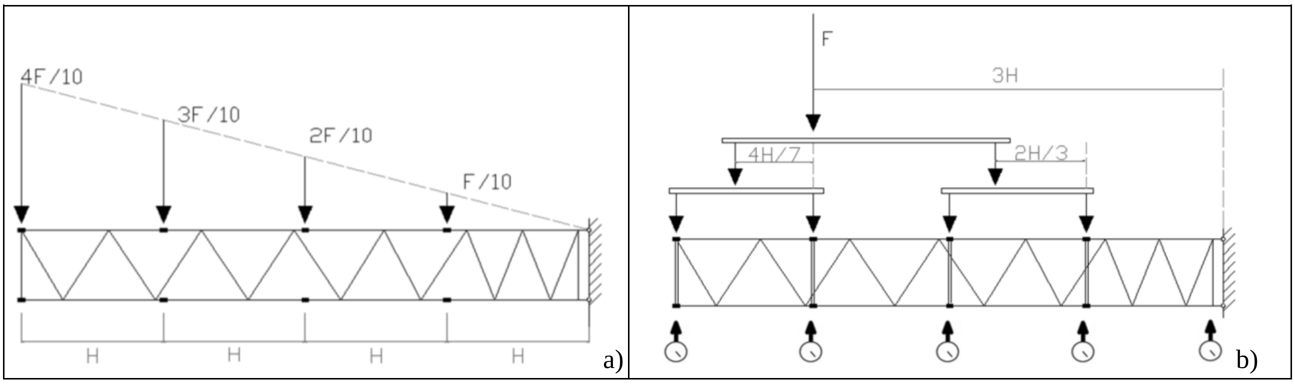

Fig. 3. a) Seismic load distribution; b) Corresponding test setup.

7 different configurations were chosen with the objective of getting a wide range of situations (design for low, moderate or high seismicity, D/Z/X type of cross bracing…). Symmetric frames are subjected to 1 push-over and 1 cyclic test, whereas asymmetric frames are subjected to 2 opposite push-over and 1 cyclic test (see *Fig. 4*).

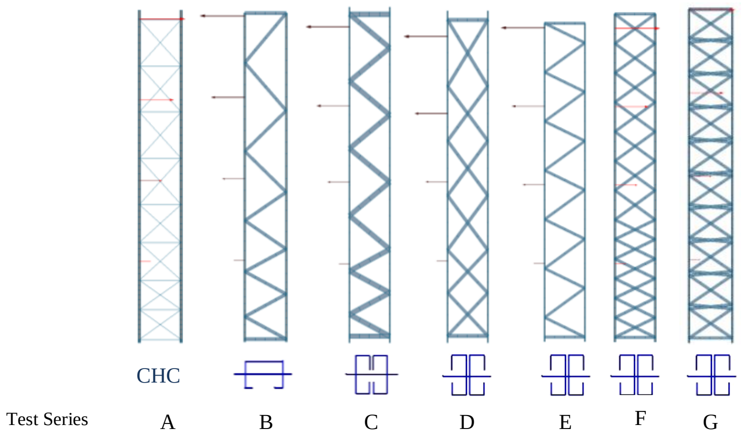

Fig. 4. Tested configurations.

For symmetrical frames, the push-over load-displacement curves are represented as push and pull tests for comparison with the cyclic test. Displacement history is expressed in terms of imposed displacement ductility, making reference to the yield displacement, generally evaluated through monotonic tests.

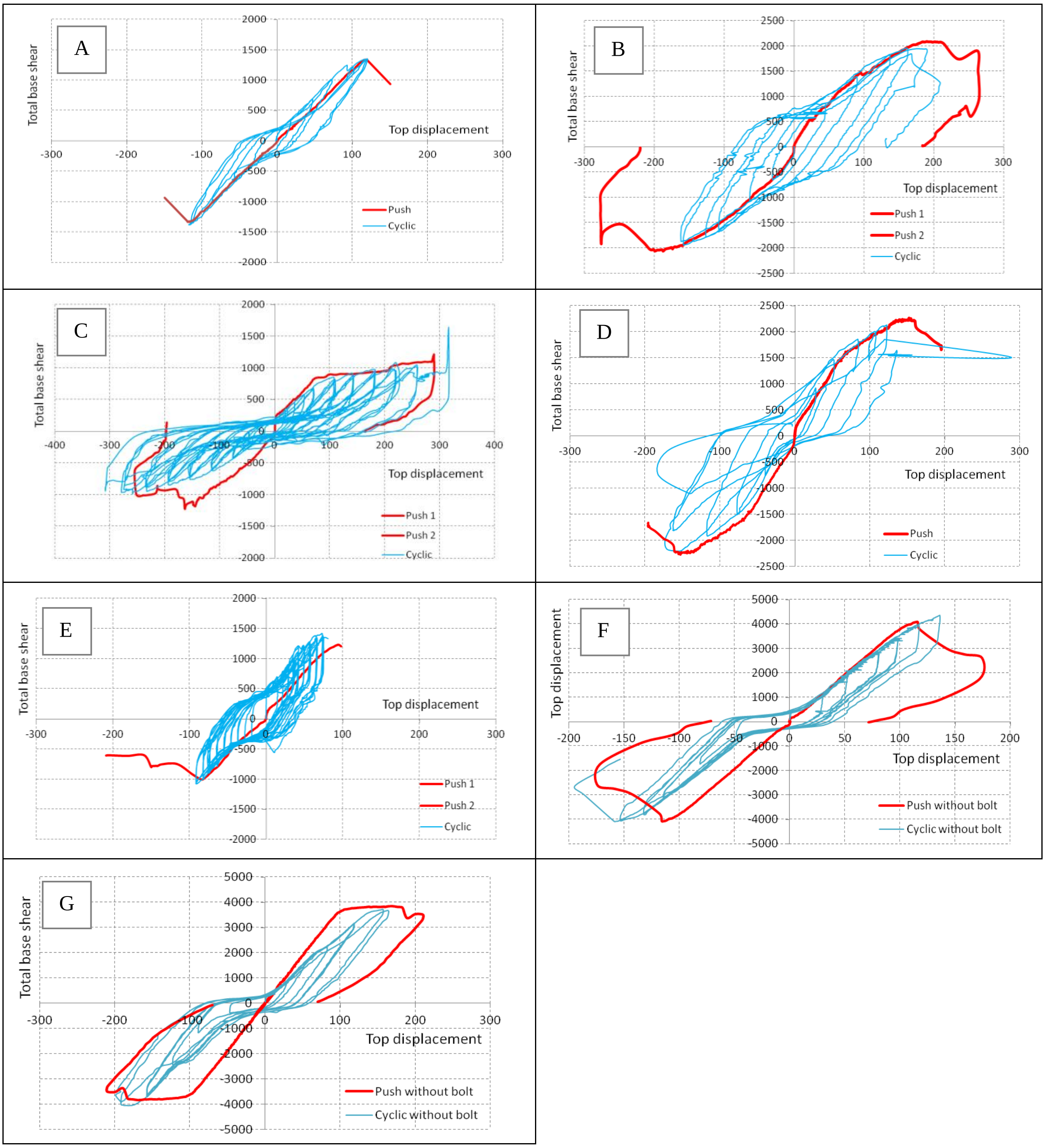

Fig. 5. Force-displacement curves for all tests series.

The failures of all cross-frames occur in their lower part:
Cross-frame A is relatively brittle; low energy can be dissipated and the ductility can be estimated equal to 1. The failure modes are local and global buckling of the diagonals in compression followed by the shearing of the bolt of the corresponding diagonals in tension.
Both push-over tests fail at the same load level for cross-frame B; the backbone curve of the cyclic test matches well with the monotonic tests. The ductility of this frame lays around 1.75. The diagonals being connected to the uprights at different connection nodes leads to additional shear in

the uprights between these 2 points which is fatal for the structure. The failure is thus a local shear of the uprights whereas the diagonals remain undamaged.
For cross-frame C the push-over curve in one direction matches perfectly the cyclic curve whereas the push-over in the other direction reaches higher loads with lower displacements. The reason might be because both push-over have been realised downwards and the cyclic down- and upwards leading to not symmetrical behaviour in terms of management of the looseness of the connections. The failure modes are bearing of the diagonals in tension, buckling of the diagonals in compression with local crushing of their extremities together with a torsional buckling of the uprights. According to both monotonic tests the ductility of this frame is expected between 1.4 and 1.6.
The monotonic load-displacement curve for cross-frame D fits perfectly the cyclic curve. The ductility of this frame estimated according to the monotonic test is 1.8 which assumes the frame to be relatively energy dissipative. The failure modes observed are torsional buckling of the uprights with buckling of the diagonals in compression and bending of their connecting bolts.
For cross-frame E the vertical shift of the cyclic test in the positive values with regard to the monotonic test is again due to the push down- and upwards for the cyclic test whereas both monotonic tests are realised pushing downwards in relation with the looseness of the diagonal to upright connections. The ductility is estimated at 1.2 and 1.3 regarding both push-over. The failure mode is a pure diagonal weakness by buckling and bearing.
Cross-frames F and G had to be released from their bolts connecting the X-bracings at mid-length because the setup would break prior to the frames. The connection at mid-length makes these frames very rigid and resistant. The failure mode is a diagonal failure by buckling for both frames. The ductility of frame F is estimated at 1.3. The load-displacement curve for frame G is a nice bi-linear curve followed by a regain in capacity and the ductility of this frame is estimated at 2.1.

2 DOWN-AISLE BEHAVIOUR

Down-aisle tests consist in 1 span – 1 level frames. The system of the longitudinal bracings is composed of vertical bracings - X bracings with extra uprights and extra horizontal element acting as a rigid frame - and horizontal bracings (see *Fig. 6*).

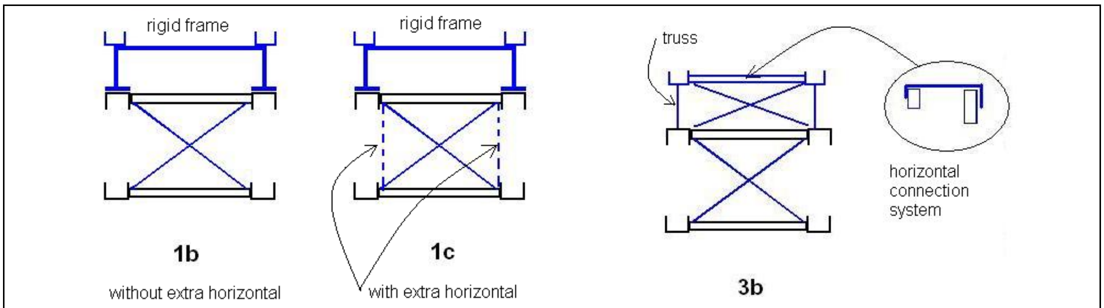

Fig. 6. Horizontal bracing system configuration.

The base-plates are welded on appropriate supports; the load is applied horizontally by means of an additional beam pushing against steel-stops welded at mid-length of the pallet-beams. This setup is realised in a way not to restrain the movement of the frame. The longitudinal displacements are measured at the 6 uprights at the pallet-beam's height.

One push-over and one cyclic test have been performed on each configuration illustrated in Figure 6 until failure of one element of the structure. No vertical load acts on the structure. Load-displacement curves have been plotted for one upright at a time: A – upright of frame opposite to vertical bracing panel; B – upright of frame attached to bracing panel (see *Fig. 7*).

Configuration 1b represents a structure designed for high seismicity. The horizontal load reaches high values before failure of the structure for a spate of different failures arising cascading:

buckling of horizontal bracing, failure of welding of beam to connector, local buckling of pallet beam, deformation of horizontal bracing connections and shearing of bolt connecting upright to base-plate. The displacement of the independent panel is double the displacement of the panel close to the bracing panel.

Configuration 1c is designed for high seismicity. The horizontal bracing is composed of a rigid panel with 2 X-bracings. The hooks of the beam-end connectors open during the tests causing the complete horizontal bracing panel to disconnect from the uprights. The presence of vertical loads or a safety pin might have avoided this issue and lead to another failure.

Configuration 3b is a structure designed for low seismicity; the failure occurs prematurely in the horizontal bracing connecting the cell to the vertical bracing panel without any other damage; the bolted assembly of the horizontal diagonal simply fails by a net rupture.

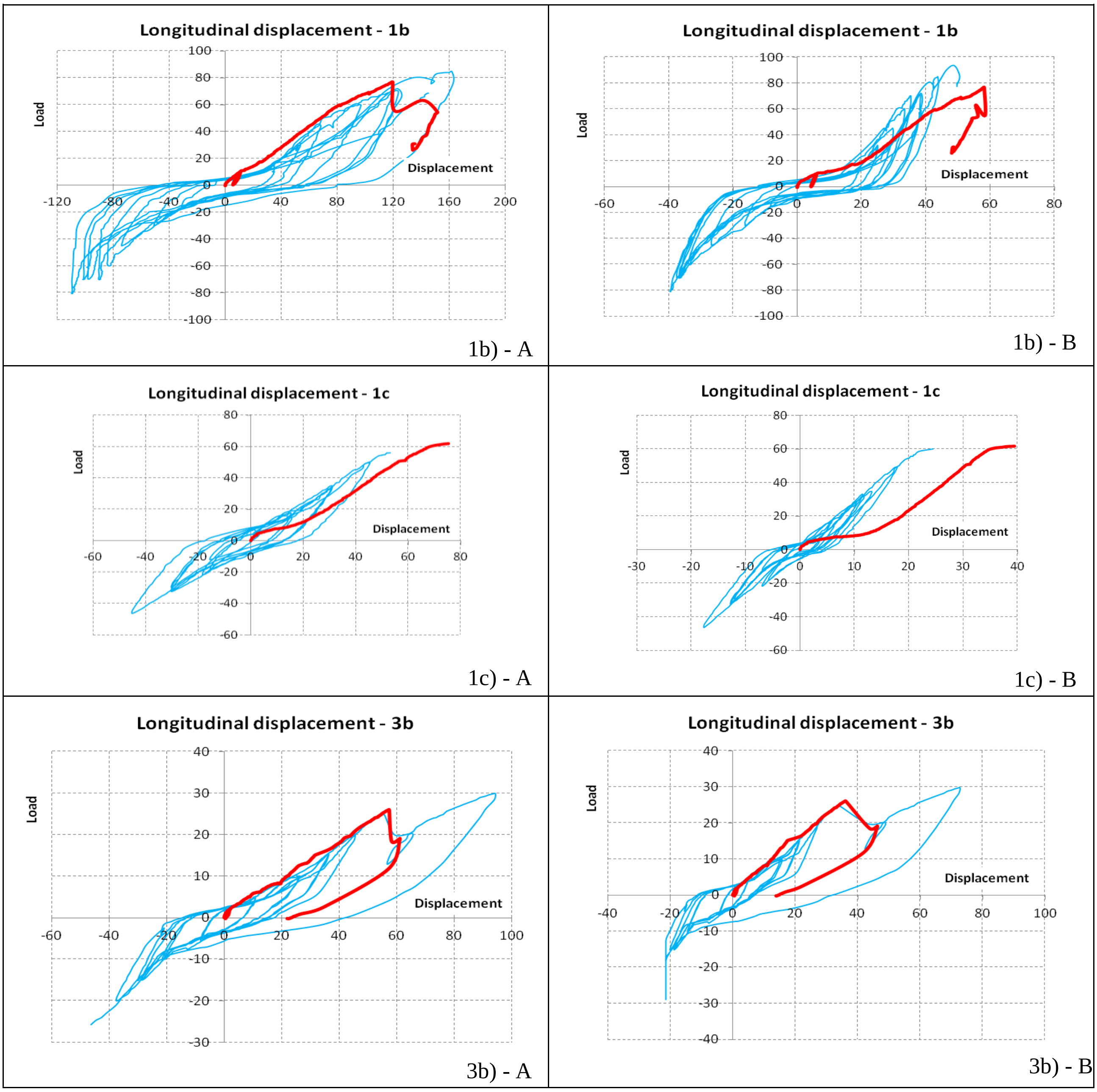

Fig. 7. Force-displacement curves for all tests series: A – measurements of independent frame; B – measurements of frame connected to bracing frame.

3 SUMMARY AND ACKNOWLEDGEMENTS

This paper has presented the general headlines of a study that aims at investigating the behaviour of cross-frames of pallet racks as well as the behaviour in down-aisle direction in presence of eccentric vertical bracings under earthquake loading. The monotonic and cyclic tests are realized on cross- and longitudinal frames with different typologies and geometrical pattern of the bracing members.
Thanks to the large variety of cross-frames tested, an interesting experimental data base has been elaborated, with ductilities varying according to the different active failure modes. Resulting values are summarized in the following *Table 1*:

*Table 1.*Summary of the tests

Series	Seismicity	Failure mode	Ductility
A	high	Diagonal: buckling + shearing of bolts	1,01
B	high	Upright: local shear at diagonal intersection	1,75
C	moderate	Diagonal: buckling + local crushing; bearing	
		Upright: torsional buckling	1,40 / 1,63
D	high	Diagonal: buckling + bending of bolts	
		Upright: torsional buckling	1,79
E	low	Diagonal: buckling + bearing	1,33 / 1,18
F	moderate	Diagonal: buckling in lower panels	1,27
G	high	Diagonal: buckling in lower panels + bearing	2,06

Longitudinal tests on 1 span – 1 level frames could conclude to different failure modes which are summarised in *Table 2*:

*Table 2.*Summary of the tests

Series	Seismicity	Failure mode
1b	high	Buckling of horizontal bracing, shear of bolt connecting upright to base-plate, failure of welding of beam to connector
1c	high	Beam-end connector: hooks get weak and jump out of notches
3b	low	Horizontal bracing: buckling and bearing

Support for this research from the European Commission, Research Fund for Coal and Steel, Steel Technical Group TGS 8 “Steel products and applications for building, construction and industry”, is gratefully acknowledged (Grant agreement RFSR-CT-2011-00031) as well as the support received from the Industrial Partners of the project, in particular for supplying the material., i.e. Modulblok (Italy), Nedcon (the Netherlands), SSI Schäffer (Germany) and Stow (Belgium).

REFERENCES

[1] EN 15512. Steel static storage systems - adjustable pallet racking systems – principles for structural design. Brussels, Belgium: European Committee for Standardization (CEN); 2009.

[2] Gilbert B.P., Rasmussen K.J.R., Baldassino N, Cudini T, Rovere L. Determining the transverse shear stiffness of steel storage rack upright frames. Journal of Constructional Steel Research; 78(2012).

[3] Degée H, Denoël V. Numerical modeling of storage racks subjected to earthquake. ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rethymno, Crete, Greece; 2007.

[4] FEM 10.2.08 – "Recommendations for the design of static steel racks in seismic conditions", version 1.00, European Racking Federation, September 2010.

[5] Degée H. New European recommendations for the design of static steel pallet racks in seismic conditions – the FEM 10.2.08 Code of Practice. Proc. of the ICTWS 2011 Conference, Timisoara (2011).

[6] EN 1998 – Eurocode 8 – "Design of structures for earthquake resistance", CEN, 2005.

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KEYWORDS: Pallet racks; seismic behaviour, experimental testing, cross-aisle, down-aisle, frame behaviour.

ABSTRACT

Prediction of the structural behaviour of pallet racks is known as a difficult task because affected by the particular geometry of their structural components, often exhibiting a highly non-linear behaviour. Due to these peculiarities, specific modelling and design rules are required for such non-traditional steel structures that cannot be considered as classical buildings. This is particularly the case for their seismic design. The most recent design standards propose therefore a combined numerical-experimental approach in which the design structural analysis is supported by specific tests to evaluate the performance of the key components (members and joints).
Results presented in this paper are part of a wide research program "Seisracks2 – Storage Racks in Seismic Areas" funded by the European Union (RFCS research program). This research program aims at constituting a scientific background document for the conversion of the Code of practice FEM 10.2.08 to a European Standard.
The present paper intends to summarize the current situation of two main aspects of this research:
(i) the investigations carried out on the cross-aisle behaviour, with the objective of covering a wide range of configurations (D/Z/X type of cross bracing including different types of connection) and to investigate their consequences on the transverse stiffness, resistance and deformation capacity;
(ii) the behaviour in down-aisle direction in presence of eccentric vertical bracings (hybrid frame/braced structural behaviour) with a significant torsional component due to the eccentricity of the bracing system with respect to the centre of mass of the stored goods.
The objectives of the study are to provide an experimental corpus available for proper calibration of numerical models and to define testing procedures suitable for the identification of the main structural parameters easily transferrable into numerical models. These various issues are investigated by means of full scale push-over and cyclic testing.
In the present study, a more realistic configuration has been chosen consisting in 8 meter high cross-frames tested transversally with 4 load levels equally distributed over the height which correspond to the beam levels of the case-studies, i.e. to levels where the masses are actually present. Vertical side guides prevent the out-of-plane instabilities. Displacement transducers are located at each beam level and at the bottom. The objective is clearly to test the frame in a real loading configuration in terms of shear and overall bending moment distribution.

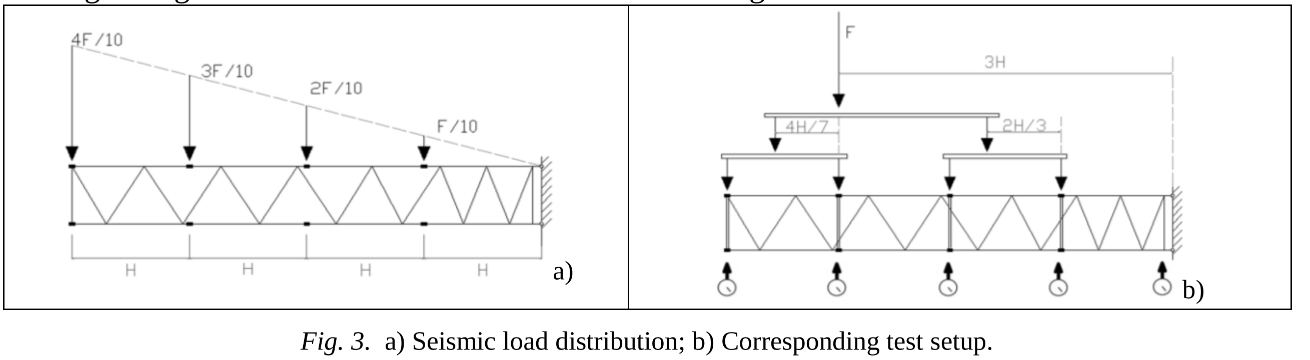

Fig. 3. a) Seismic load distribution; b) Corresponding test setup.

Down-aisle tests consist in 1 span – 1 level frames. The system of the longitudinal bracings is composed of vertical bracings - X bracings with extra uprights and extra horizontal element acting as a rigid frame - and horizontal bracings. The load is applied horizontally by means of an additional beam pushing against steel-stops welded at mid-length of the pallet-beams. The displacements are measured at 10 different positions: longitudinal displacements of the 6 uprights and transversal displacements of the 4 external uprights, all at the pallet-beam's height.

CONCLUSIONS

Table 1 summarises the results of the cross-aisle tests, i.e. the design level of seismicity, the failure mode observed and the estimated ductility.

Table 1. Summary of the cross-aisle tests

Series	Seismicity	Failure mode	Ductility
A	high	Diagonal: buckling + shearing of bolts	1,01
B	high	Upright: local shear at diagonal intersection	1,75
C	moderate	Diagonal: buckling + local crushing; bearing	
		Upright: torsional buckling	1,40 / 1,63
D	high	Diagonal: buckling + bending of bolts	
		Upright: torsional buckling	1,79
E	low	Diagonal: buckling + bearing	1,33 / 1,18
F	moderate	Diagonal: buckling in lower panels	1,27
G	high	Diagonal: buckling in lower panels + bearing	2,06

The failure modes observed during the down-aisle tests are summarised in *Table 2*:

Table 2. Summary of the down-aisle tests

Series	Seismicity	Failure mode
1b	high	Buckling of horizontal bracing, shear of bolt connecting upright to base-plate, failure of welding of beam to connector
1c	high	Beam-end connector: hooks get weak and jump out of notches
3b	low	Horizontal bracing: buckling and bearing

ACKNOWLEDGMENT

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REFERENCES

[1] EN 15512. Steel static storage systems - adjustable pallet racking systems – principles for structural design. Brussels, Belgium: European Committee for Standardization (CEN); 2009.

[2] Gilbert B.P., Rasmussen K.J.R., Baldassino N, Cudini T, Rovere L. Determining the transverse shear stiffness of steel storage rack upright frames. Journal of Constructional Steel Research; 78(2012).

[3] Degée H, Denoël V. Numerical modeling of storage racks subjected to earthquake. ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rethymno, Crete, Greece; 2007.

[4] FEM 10.2.08 – "Recommendations for the design of static steel racks in seismic conditions", version 1.00, European Racking Federation, September 2010.

[5] Degée H. New European recommendations for the design of static steel pallet racks in seismic conditions – the FEM 10.2.08 Code of Practice. Proc. of the ICTWS 2011 Conference, Timisoara (2011).

[6] EN 1998 – Eurocode 8 – "Design of structures for earthquake resistance", CEN, 2005.