SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

EXPERIMENTAL STUDIES ON THE SEISMIC PERFORMANCES OF STEEL STORAGE RACKS

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ABSTRACT

The paper focuses on the seismic behavior of static steel pallet racks used for storage of various types of goods and located in areas of retail warehouse stores and other facilities, possibly accessible to the public. Storage racks are composed of specially designed cold-formed steel elements that permit easy installation and reconfiguration. Prediction of the structural behavior of pallet racks is difficult 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 beam-to-upright and base-plate joints exhibit a strongly non-linear behavior. Due to their peculiarities, specific modeling and design rules are required for these non-traditional steel structures that cannot be considered as classical building. The design is even more complicated for storage racks installed in seismic zones, where they must be able to withstand horizontal and vertical dynamic forces.

The innovative items that are presented hereby deal essentially with advances in the understanding of the behaviour in cross-aisle direction on the one hand, depending on the configuration and the type of connection of bracings with the upright frames, and in down-aisle direction in presence of eccentric vertical bracings in the other hand. These two apsects are investigated by means of full scale push-over and cyclic testing, component push-over and cyclic testing of racking systems.

INTRODUCTION

Racking systems are not regular buildings but a very particular form of steel construction. They differ from buildings in terms of their use, the loads that are supported, the geometrical dimensions and the components used in their construction. These components are normally thin-gauge cold-formed profiles and, in the case of uprights, are typically continuously perforated. This gives the required functionality, adaptability and flexibility needed to cope with the great variation in the different types of goods that are stored.

Prediction of the structural behavior of pallet racks is difficult 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 modeling and design rules are required for these non-traditional steel structures, especially for the beam-to-upright and base-plate connections in the longitudinal down-aisle direction, that exhibit a

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strongly non linear behavior. In the cross-aisle direction, stability is ensured by frames consisting of two uprights connected by bracing members as shown in Fig.1:

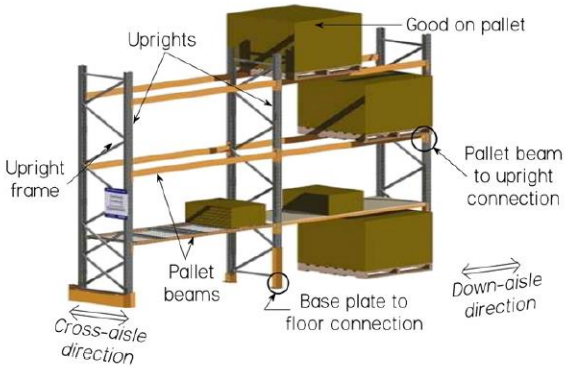

Figure 1. Typical storage rack configuration

Rack design is even more complicated for storage racks installed in seismic zones, where they must be able to withstand horizontal and vertical dynamic forces and where, besides the usual global and local collapse mechanisms, additional limit states such as for instance the fall of the pallets with subsequent damage to goods, people and to the structure itself must be considered.

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 as such the "general design rules" (applicable to ordinary steel structures) for 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. For instance, many specific physical phenomena strongly affect the structural behavior of a racking system during an earthquake, such as the energy dissipated in the deformation of stored goods or when pallets slide on their supports.

From a theoretical point of view, racking structures can be designed according to low dissipative or to dissipative design. However, their peculiar typology makes a dissipative design rather difficult and for sure uneconomical. The practice is thus to follow a non-dissipative design procedure, although not recommended for high seismicity. It is therefore of prime importance to understand and control properly the structural behavior in order to estimate as accurately as possible the capacity of the system and to prevent any failure mode that could induce catastrophic failure of the entire storage facilities.

In this perspective, in the context of the RFCS European research program Seisracks2, experimental tests have been carried out on sub-structures at the Material & Structures Laboratory of University of Liège. Two series of tests have been carried out in order to investigate:

- The behaviour of cross frames,
- The basic load transfer mechanisms from the main rack to the spine bracing required in most cases in order to provide the system with sufficient stiffness and resistance in the longitudinal direction.

Regarding the cross-frames, tests are carried out under static pushover and cyclic conditions. The results are essentially exploited in terms of characterization of collapse modes. They are also compared with tests obtained from standardized shear tests and the effect of cyclic degradation is evaluated. 19 tests have been carried out as a whole (12 pushover and 7 cyclic tests) on 7 different structural configurations, each of them characterized by a different targeted failure modes. These cross-frames are 8 meters high but tested horizontally for experimental easiness. The loading system is represented on the left hand side of Fig.2, while the right hand side shows the different geometrical configurations considered (D/Z/X type of cross bracing including different types of connections).

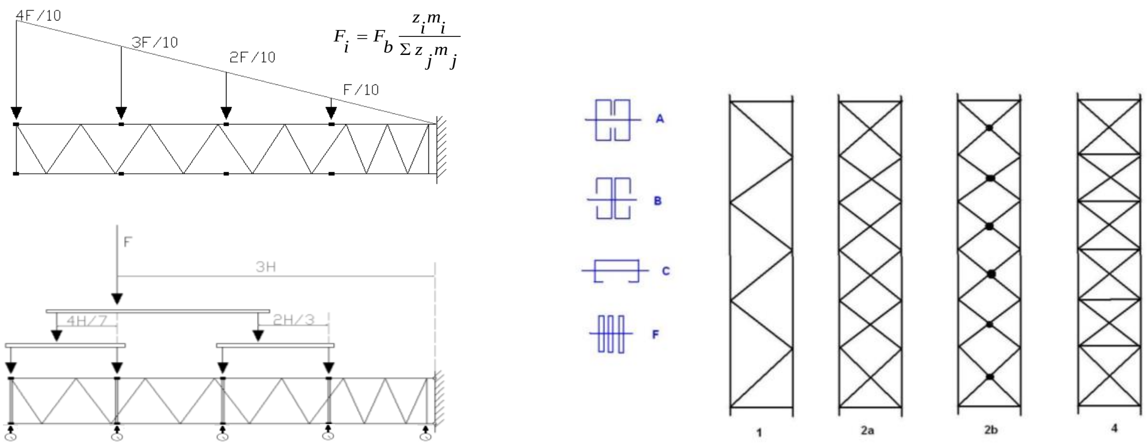

Figure 2. Typical cross-frame test specimens and loading system

Regarding the longitudinal frames, 7 tests have been carried out (4 pushover and 3 cyclic tests). The main focus of the testing campaign is put on the load transfer mechanism from the longitudinal moment frame to the rear spine bracing. Therefore, 4 different types of load transfer configurations have been investigated, as shown on Fig.3.

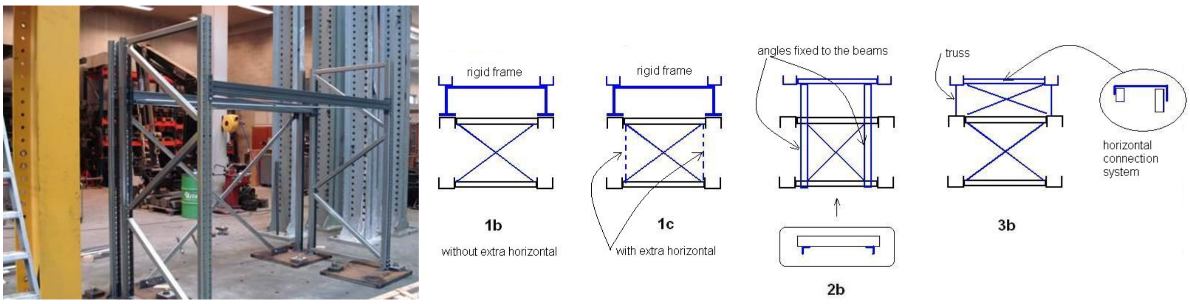

Figure 3. Typical specimen for longitudinal tests

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 and design procedures.

TEST SETUP AND SPECIMENS FOR THE CROSS-AISLE DIRECTION

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. In the recommended test setup, shown in Fig.4, an upright frame composed of at least two bracing panels is restrained in the transverse direction at 2 corners. One upright is pinned in the longitudinal direction at one end and a longitudinal load F is applied at the opposite end of the other upright through its centroidal axis.

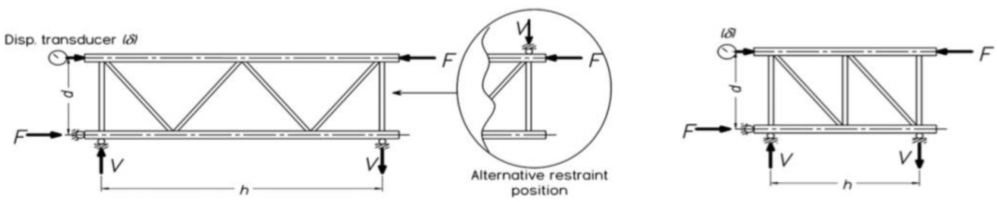

Figure 4. Upright frame shear stiffness setup in EN 15512 [1].

This test is however characterizing the behavior 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 with the perspective of assessing the transverse stiffness, resistance and deformation capacity of cross-frames under realistic seismic loading conditions; the cross-frame tests are carried out on specimens similar to those classically used for the characterization of the pure shear behavior (although longer) but with an adapted loading. Tests are carried out statically ("pushover tests") and cyclically under transverse loading representative of the earthquake action.

Industrial partners involved in the project were invited to provide at least one configuration out of different suggested types with the objective of getting a wide range of situations (design for low, moderate or high seismicity, D/Z/X type of cross bracing…). For confidentiality reasons the names of the Industrial Partners are not given here nor the details of the profile sections.

In the present study, a more realistic configuration has been chosen (although complicating the setup) consisting in 8 meter high frames tested transversally with 4 load levels equally distributed over the height of the frame with a constant spacing of 2 m (this is illustrated on the left hand side of Fig.2). The load levels correspond to the beam levels of the case-studies configurations, i.e. to levels where the masses are actually present. Vertical side guides are placed at each of these levels to prevent out-of-plane instabilities. The objective is clearly to test the frame in a real loading configuration in terms of shear and overall bending moment distribution.

In practice, the loads are indirectly applied on the structure by means of one single jack F acting on a distribution beam that is acting then on two other beams, in such a way to have a linear triangular distribution. Loads act directly on the upper side when pushing downwards; transfer hoops are foreseen to distribute the load to the lower upright when pulling. No direct axial force is applied on the uprights, implying the base connection to be designed, and if necessary reinforced 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 next to the bottom horizontal bracing member and at each beam level. Two extra transducers measure the relative displacement between uprights at the first two beam levels.

7 different configurations were chosen out of 4 basic typologies with 4 types of diagonal-to-upright connections (see Fig. 2). For symmetric configurations (Test series A, D, F and G), 1 pushover and 1 cyclic test are planned, whereas for asymmetric configurations, (Test series B, C and E), 2 pushover (one in each direction) and 1 cyclic test will be carried out, see Fig. 5.

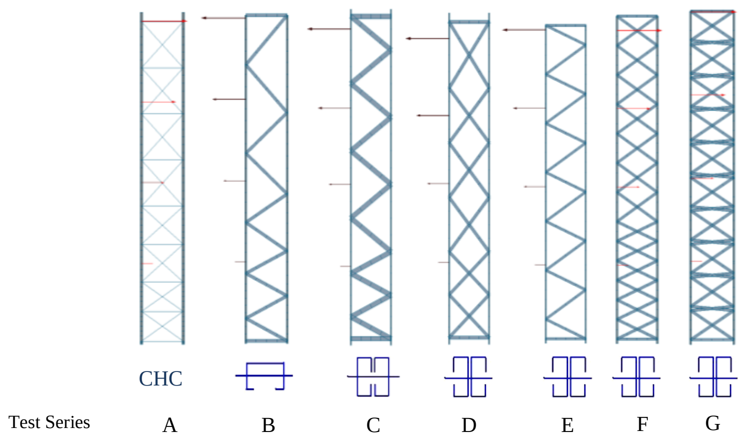

Figure 5. Tested configurations.

The behaviour of the upright-to-base-plate connection is intended to be covered by the research project Seisracks2 but with tests that are not discussed here. The aim of the study presented in this paper is specifically to emphasize on structural failure modes of the cross-frame either in the upright or in the bracing members but not in the upright-to-base-plate connection which is tested separately.

TEST RESULTS

As the present tests were meant to be realized without direct axial forces acting on the uprights the uprights-to-base-plate connections had to be reinforced in order to avoid a preliminary failure of these connections due to tension instead of decompression. Indeed the base connections are designed taking into account vertical efforts. Transversal load usually leads to extra compression in one connection and decompression in the other one which is not the case here. Uprights are therefore welded to the base-plates all along their profile, see Fig.6.

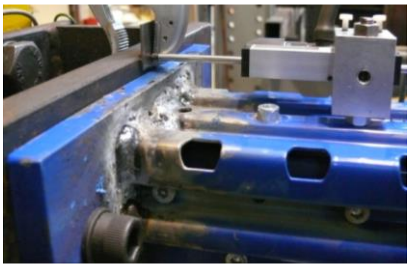

Figure 6. Upright welded to base-plate.

For confidentiality reasons towards the Industrial Partners, the results will not appear clearly in this paper; only the measurements of the top level are presented vs. the applied load but without units. For symmetrical frames the push-over load-displacement curves are represented as push and pull tests for comparison with the cyclic test.

Usually the specimens are subjected to a symmetrical reversed cyclic displacement history; displacement history is expressed in terms of imposed displacement ductility, making reference to the yield displacement, generally evaluated through monotonic tests. Testing procedure is composed by single fully reversed cycles at displacement ductility of ¼, ½, ¾ and 1, followed by a sequence of groups of two (or three) cycles at multiples (2, 3, 4, etc.) of a yield displacement until a conventional failure criterion is met. For sake of easiness, the cyclic tests have been load-controlled with procedure sometimes adapted according to the measured displacements and the observations in order to avoid a premature failure.

TEST SERIES A

This cross-frame is designed for high seismic zone. As seen on Fig.7 this frame is relatively brittle, low energy can be dissipated and the ductility can be estimated equal to 1.

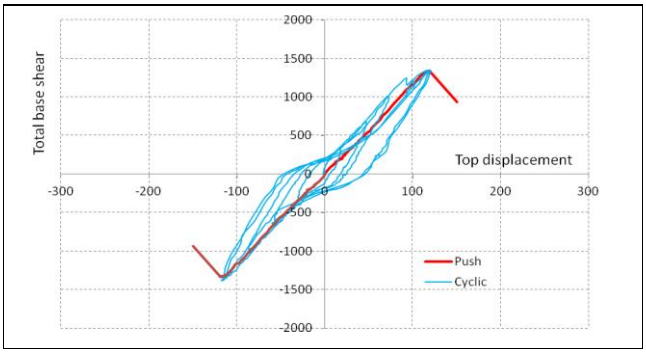

Figure 7. Force-displacement curve for test series A.

The failure modes are the following:
- local and global buckling of diagonal in compression;
- shearing of bolt of diagonal in tension.

TEST SERIES B

This cross-frame is designed for high seismic zone. Both push-over tests fail at the same load level as seen in Fig.8. The ductility lays around 1.75. The cyclic test matches well with the monotonic tests.

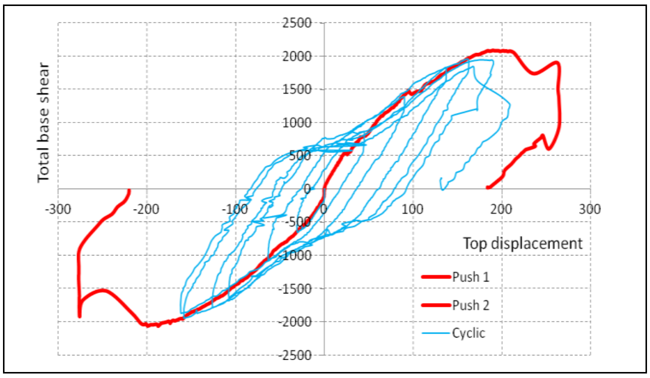

Figure 8. Force-displacement curve for test series B.

The failure modes observed are the following:
- local shear at diagonal intersection as they do not converge neither to the same connecting point nor to the centroïd of the upright cross-section;
- diagonals remain intact.

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.

TEST SERIES C

This cross-frame is designed for moderate seismic zone. The push-over curve in one direction matches perfectly the cyclic curve whereas the push-over curve in the other direction reaches higher loads with lower displacements, see Fig.9. The reason of this 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.

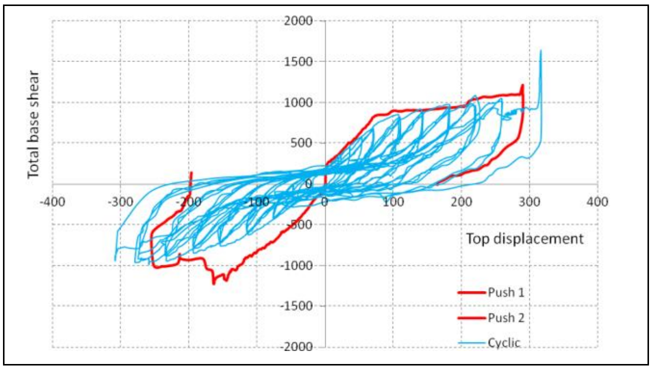

Figure 9. Force-displacement curve for test series C.

The failure modes are the following:
- bearing of diagonal in tension;
- buckling of diagonal in compression + local crushing of diagonal's extremities;
- torsional buckling of uprights.

According to both monotonic tests the ductility of this frame is expected between 1.4 and 1.6.

TEST SERIES D

This cross-frame is designed for high seismic zone. The monotonic load-displacement curve fits perfectly the cyclic curve, see Fig.10.

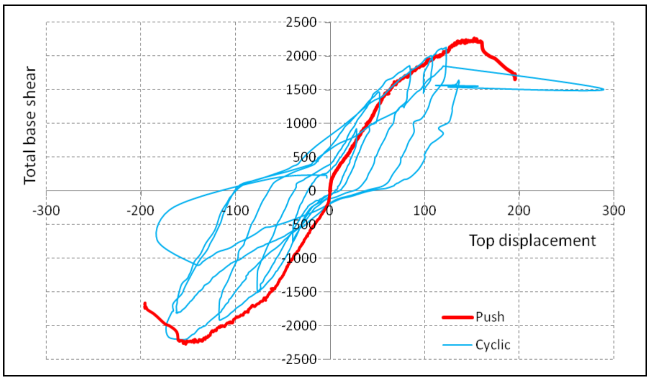

Figure 10. Force-displacement curve for test series D.

The failure modes are the following:

- buckling of diagonal in compression;
- bending of bolts;
- torsional buckling of uprights.

The ductility of this frame estimated according to the monotonic test is 1.79 which assumes the frame to be relatively energy dissipative.

TEST SERIES E

This cross-frame is designed for low seismic zone. As the ductility estimated regarding both monotonic tests lays between 1.2 and 1.3 it was decided to cycle increasing the load progressively to avoid a premature failure during this test, see Fig.11.

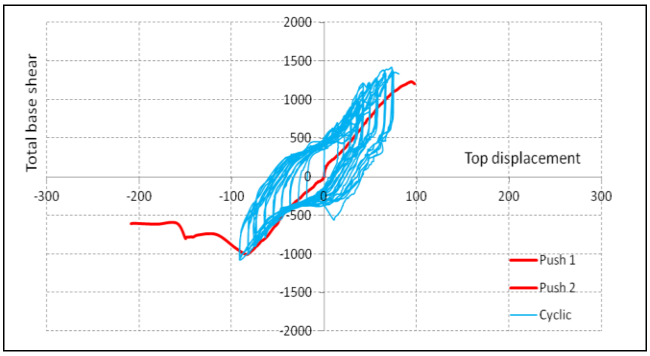

Figure 11. Force-displacement curve for test series E.

The vertical shift of the cyclic test in the positive values with regard to the monotonic is again due to the push down- and upwards for the cyclic test whereas both monotonic are realised pushing downwards in relation with the looseness of the diagonal to upright connections.

The failure modes are the following:

- buckling of diagonal in compression;
- bearing of diagonal in tension.

TEST SERIES F

This cross-frame is designed for moderate seismic zone. The test in its designed configuration had to be stopped for a certain load level because the test setup would brake instead of the tested frame. The X-bracings being connected at mid-length makes this cross-frame very rigid and resistant. It remains almost in the elastic domain as shown on Fig.12. The bolts connecting the diagonals at mid-length have thus been removed and the frame was retested; it finally failed at the same load level, see Fig. 13. The ductility of this frame is estimated at 1.3.

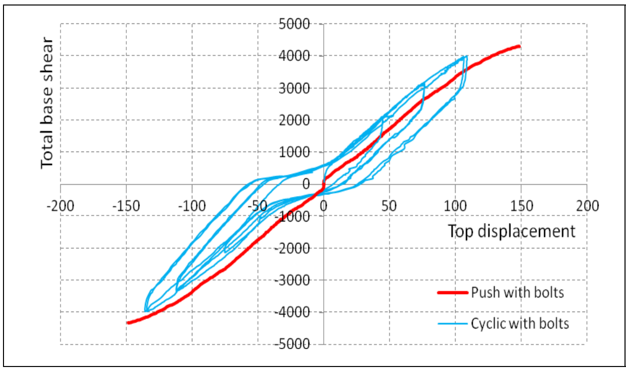

Figure 12. Force-displacement curve for test series F – with bolt.

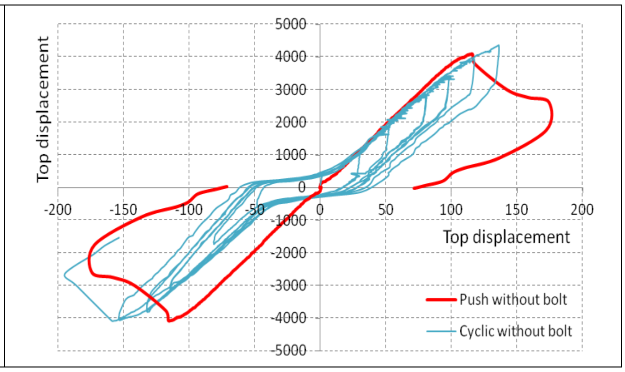

Figure 13. Force-displacement curve for test series F – without bolt.

The failure mode is the following:

- buckling of diagonals of all lower panels with a bend at mid-length.

TEST SERIES G

This cross-frame is designed for high seismic zone. The test had to be stopped before failure because of the stiffness of the frame due to the X-bracings connected at mid-length. The applied load reached the maximum the test-setup could withstand. Once the frame back to its horizontal position, the bolts have been removed and the test reiterated. The load-displacement curves of both tests are illustrated in Figures 14 and 15.

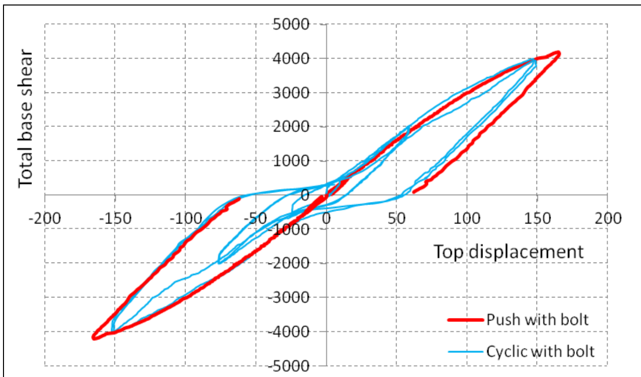

Figure 14. Force-displacement curve for test series G – with bolt.

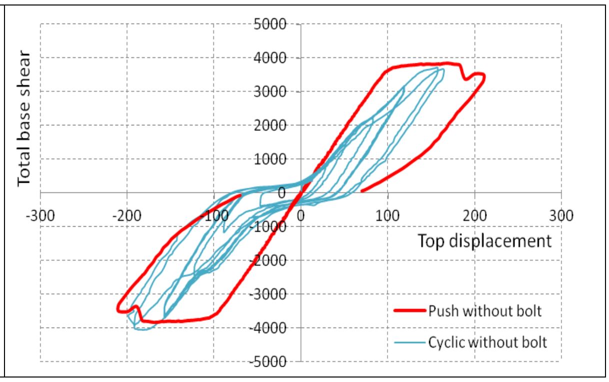

Figure 15. Force-displacement curve for test series G – without bolt.

The load-displacement curve of the unbolted cross-frame is a nice bi-linear curve followed by a regain in capacity. The ductility of this frame can be estimated at 2.1.

The failure modes are the following:

- buckling of diagonals of lower panels;
- bearing of diagonals in tension.

TEST SETUP AND SPECIMENS FOR THE DOWN-AISLE DIRECTION

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 details of components and the types of connections of the horizontal bracing are shown in Fig.3. 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 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.

TEST RESULTS

One push-over and one cyclic test have been performed on each structure. The test is realized without vertical payload, the horizontal load is increased until failure of one element of the structure. Many measurements have been realized but only 2 are presented here: the longitudinal displacement of both uprights of the rear cross-frame:

- measurements A: upright of frame opposite to vertical bracing panel;
- measurements B: upright of frame attached to bracing panel (see Fig.16).

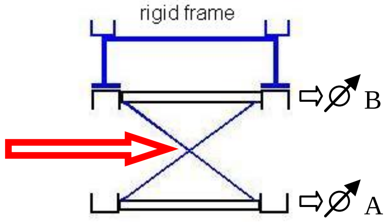

Figure 16. Test setup and location of measurements A and B.

TEST SERIES 1b

This structure is designed for high seismic zone. The failure mode observed during this test is buckling of horizontal bracing, shear of bolt connecting upright to base-plate, failure of welding of beam to connector.

The force-displacement curve is relatively linear and the failure is brittle as can be seen in Fig.17:

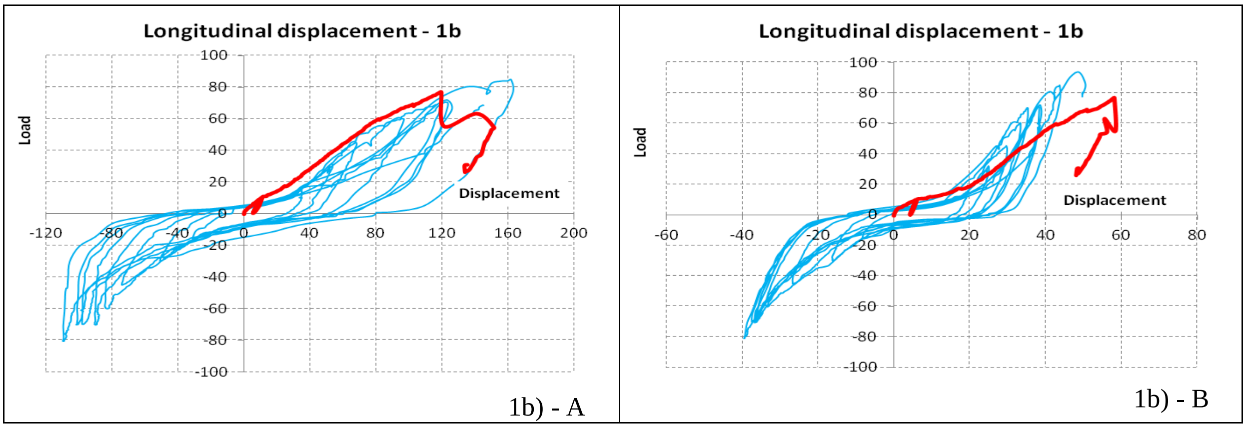

Figure 17. Force-displacement curves for tests series 1b

TEST SERIES 1c

This structure is designed for high seismic zone. The failure is concentrated at the beam-to-upright connection: hooks get weak causing the beam to jump out of the notches. Fig.18 illustrates the load-displacement curves observed during this test.

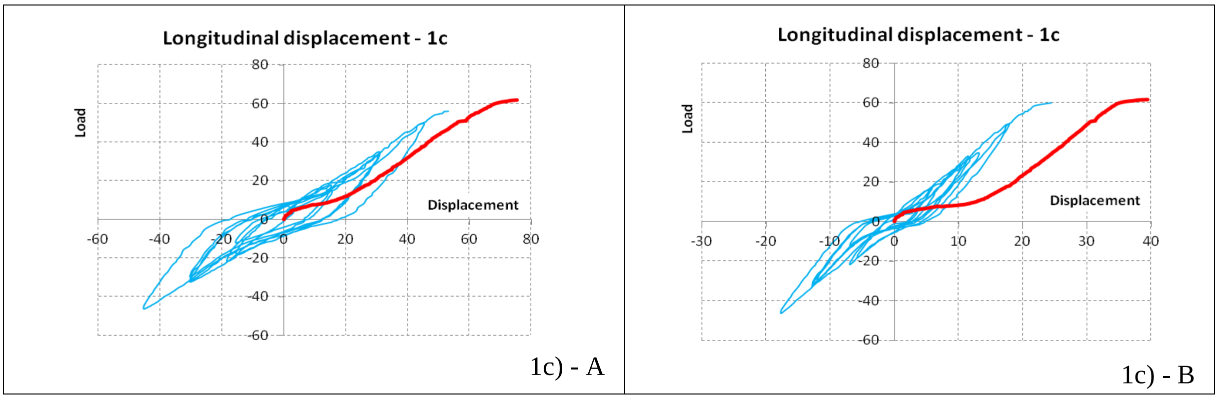

Figure 18. Force-displacement curves for tests series 1c

TEST SERIES 3b

This structure is designed for low seismic zone. The failure occurs due to buckling and bearing of the horizontal bracing members and the load-displacement curve is illustrated in Fig.19.

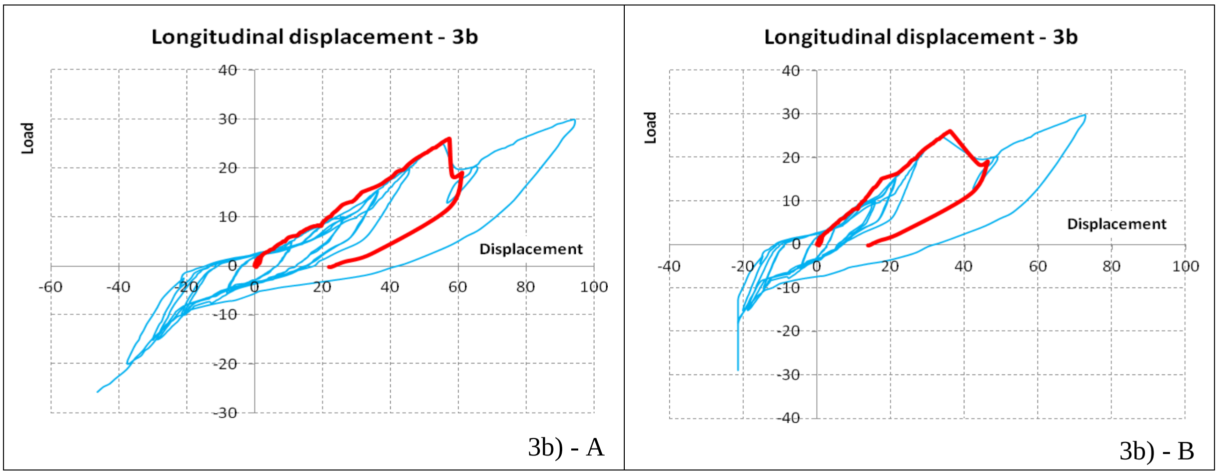

Figure 19. Force-displacement curves for tests series 3b

CONCLUSIONS

This paper has presented the general context of a study that aims at investigating the behavior of cross-frames and longitudinal frames of pallet racks under earthquake loading. More specifically, the paper presents the results of the monotonic and cyclic tests realized on cross-frames with different typologies of diagonal-to-upright connections and geometrical pattern of the bracing members and on 1-span-1-level braced longitudinal frames with different types of configurations of the load transfer to the eccentric spine bracing. In parallel to these tests, simple elastic numerical analyses of all frames have been performed in the perspective of calibrating the stiffness of the bracing members. The reduction of the cross-sectional area of the diagonals calibrated to match with the tests could be further compared with the values obtained from standard shear tests, which is however of no ease because they should be modulated according to the paneling of the structural system. Indeed the standard shear tests advocate a number of two bracing panels, which in general are identical, whereas the present cross-frames are 8 meters long with a minimum of 5 bracing panels which often stretch over the height of the frame. Furthermore the tested combination upright-diagonal regarding the geometrical properties and the paneling do not match with those used in the standard test such as the comparison would just be approximate. Thanks to the large variety of cross-frames tested, an interesting experimental data base has been elaborated, with measured ductilities varying according to the different active failure modes. Resulting values are summarized in the Table.1:

Table 1.Summary of the tests on cross-frames

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 longitudinal tests are summarized with their failure modes 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

This paper would indeed be of more direct interest with information concerning the profile geometries, diagonal-to-upright and upright-to-base-plate connections, some pictures and numerical values. But with respect to the industrial partners these information have to remain confidential.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the RFCS program of the European Commission (Grant Agreement RFSR-CT-2011-00031 – SEISRACKS2). In particular, the good cooperation with the different academic partners (Politecnico di Milano, RWTH Aachen and NTU Athens) is deeply acknowledged, as well as the continuous support received from the 5 Industrial Partners.

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