Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 2934-2942

ECCOMAS
Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

EXPERIMENTAL TESTING CAMPAIGN AND NUMERICAL MODELLING OF AN INNOVATIVE BASE-PLATE CONNECTION FOR PALLET RACKING SYSTEMS

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Abstract. *The problem of the high fragility of upright frames of pallet racking systems against lateral forces raises an important question for researchers. This lack of seismic performance can be attributed to a small degree of internal overdetermination of the system, as is also acknowledged by the European Standard for adjustable pallet racking structures (EN16681), which only takes into account the low-dissipative behaviour for these structures. This paper presents an innovative base-plate connection that can provide the upright frames of pallet racking systems with a certain degree of global ductility, thus improving the seismic attitude of these structures when seismically stimulated along the cross-aisle direction. A design procedure for the specimens to be tested is proposed, which aims at guiding the system design toward localizing yielding strains in the plates of the base connections, as the principles of the capacity design posit. The proposed base-plate connection is tested under monotonic and cyclic loads to better understand its properties and, by inference, its dynamic characterization, which could be utilized in a lighter numerical model in order to study overall performance improvement. Additionally, a numerical model of the specimen, as tested in the Laboratory of Steel Structures at the National Technical University of Athens (Greece), which has been calibrated and validated in accordance with experimental tests results, is presented.*

Keywords: Steel Structures, Adjustable Pallet Racks, Seismic Standards, Eurocode

ISSN:2623-3347 © 2021 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8687.19514

1 INTRODUCTION

The structural frames of racking structures are often composed of open cold-formed thin-walled steel members, that typically do not guarantee plastic capacities of their cross section [1, 2]. This poses a new issue: it is well-known that the capacity of structure systems to resist seismic actions in the nonlinear range generally permits their design for forces smaller than those corresponding to a linear elastic response. Another issue is related to the behaviour of structures in the post-elastic range; it becomes vital to control the force distribution [3] in order to control the structure collapse, as well the lateral displacements [4, 5] Such approach is what allows designing building with design spectra [see 6], which generally correspond to an onset of elastic spectra by introducing a conventional parameter that accounts for the capacity of the structure to dissipate energy. Nevertheless, storage racks can still provide a degree of energy dissipation if other non-conventional mechanisms are considered [7, 8, 9]. For example, if designed so, beam-to-column and base-plate connections can exhibit an inelastic behavior which could be used to keep using the same approach [10, 11]. Nonetheless, the European Framework for steel structures does not allow yet to concentrate any damage on beam-to-column connections [12].

Cross-aisle frames often have a truss-like structure system: two uprights are laced up by different diagonal patterns, the most common of which are X-shaped diagonal and D-shaped diagonal. The cross-aisle structural scheme tends to have fewer internal degrees of freedom, thus making fragile collapse modes most likely. Hence, as also shown by many works [13], the lateral resistance of the overall frame is greatly affected by the flexural behaviour of the base-plate connections, which may be as well the only place where plastic deformation can safely take place [14]. The high lateral stiffness of the upright frames is also cause of concern for the happenstance of excessive accelerations at decks level. It is safe to say that the sliding of pallets on the supporting beams can be the most serious threat to the shedding of goods, which can either endanger the health of workers/customers or even damage some structural parts thus leading to cascading effects. In the cross-aisle direction, the fundamental period is generally short, comprised between 0.7s and 1.0s [15].

The seismic responses of the two principal directions of pallet racking structures are rather different. In the down-aisle direction, the great flexibility provided by connections and the absence of spine bracings reflect in significantly high value of the fundamental period of vibrations

(a) (b)

Figure 1: (a) and (b) Warehouse stores with pallet racks (courtesy of NEDCON B.V.).

(T), sometimes up to 3.50s, which are the typical values observed for high-rise and tall steel buildings. The adherence of this structural scheme with ordinary structures has made a great body of research focus on this subject and its performance is well understood although it needs to manage a great variety of numerical special features [16].

Under lateral dynamic loads, owing to the presence of open thin-walled cross-sections, rack bearing elements are often prone to local and/or distortional buckling phenomena, which largely precede the attainment of the cross section yielding capacity. Therefore, to enforce classical design procedure, it is important to rely exclusively on the post-yielding capacity of connections. Cross-aisle frames can hardly locate plastic deformations within their inner connections, though it might be possible to design such a connection with that in mind. On the other hand, the connections between upright and building slab are characterised by a very limited degree of flexural stiffness and bending resistance, mainly limited by the column cross-section ultimate resistance capacity. In most of the cases, when the cross-aisle direction is considered, the seismic action can pose a risk for the overturning, which becomes the most dangerous limit state. Nevertheless, as it happened for the beam-to-column connections, the nonlinear cyclic behaviour can provide a non-negligible ductility to the structure. For this reason, as suggested by [17], attention must be paid on the design of base-connections to be allowed to use a behaviour factor q grater than 1 (but however lower than 2) in the seismic structural analysis;

Upright frames can be designed as *low-dissipative structural behaviour* (DCL), as recognised by EN 16681. This circumstance is addressed by EC8, and a *behaviour factor* is as well allowed, used to allow designers to perform elastic analyses and, at the same time, account for nonlinear phenomena. EC8 clearly identifies the use of $q \leq 1.50$ for this class. It is stated that such value accounts for overall structural *overstrengths*. With reason, for example, for DCL class, it is advised to avoid cross sectional class 4, for it does not guarantee enough overstrength. In contrast with this last clause, EN 16681 affirms that the behaviour factor accounts for the *energy dissipation capacity* of the structure.

This work presents the results of a experimental tests and numerical simulations to investigate the cyclic response of a base-plate connection designed for adjustable pallet racking systems. The experimental tests, which were carried out in the Laboratory of Steel Structures, NTUA (Athens, Greece), are described, and results for a monotonic and a cyclic load path are reported. Hence, the specimen was reproduced in a mesh-based numerical framework, giving further insight about the mechanical behaviour of the specimen under study.

2 EXPERIMENTAL CAMPAIGN

2.1 Specimen

A base-plate connection for adjustable pallet racking systems was conceived to provide structures with energy-dissipation capacity. The behavior of this type of connection is reminiscent of a T-stub mechanism mainly subjected to axial load, which is generally used to model the top and bottom tee of beam-to-column connections; in such situations, the working principles are well-understood and the performance under cyclic loads proved to be quite remarkable (Piluso and Rizzano 2008) [18]).

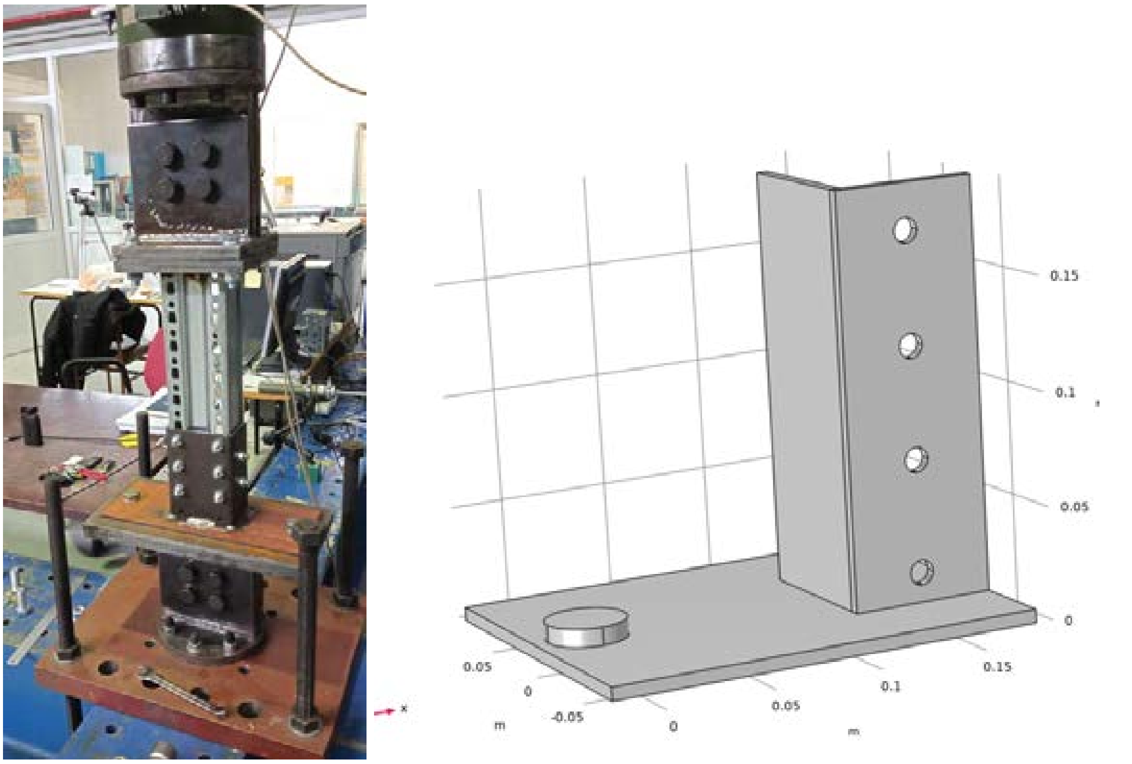
All specimens have been assembled by welding steel plates composing the base plate, 6mm thick, and the bracket, 5mm thick, made of S235 ($f_y = 235M \cdot Pa$ and $f_u = 415M \cdot Pa$) steel fastened through the flanges by means of two M20 bolts made of 8.8 class high strength steel [6]; the upright, supplied by NEDCON B.V. (The Netherlands), having an overall depth of 120 mm and an overall width of 94 mm, was made of steel S350D and is connected to the bracket by means of 8 M8 bolts 8.8 class. The photographic image and the schematic view representing the test specimen are given in Fig. 2. In order to guarantee an optimal stress distribution in the profile, the upright was cut 425 mm long ($\approx$ four times its depth). Its upper cross section is welded to an end-plate that is hence bolted to the actuator head, where the load cell is located.

The base-plate connection was tested under monotonic and cyclic loads in the Laboratory of Steel Structures, NTUA (Athens, Greece). In Fig. 2(a), the experimental setup is shown, where the testing machinery and the specimen are indicated. The static actuator has a stroke of ± 150mm and can reach up to $300kN$; the accuracy of measuring equipment belongs to the 1 class of accuracy, thus giving an expected error on the measurement of ± 1.5kN. Aiming at assessing the axial performance solely, the degree of freedom activated by the actuator is along the axis of the column stub (vertical).

2.2 Results

The monotonic test was performed by applying a displacement time history from $0 - 28$ mm, with a constant velocity equal to $v = 0.15$mm/s. The cyclic protocol was defined in accordance with the AISC Seismic Provisions (AISC 2002), which provides a test sequence given as a function of the peak deformation δ_y, with a decreasing number of cycles as the load step increases (Fig. 3(a)). The specimens were instrumented with two LVDTs located on both sides of the base plate to measure the uplift displacement.

The results of the tests are reported in Fig. 3. The two tests show an overall good agreement in terms of overall behaviour, providing good performance accounting for the cyclic consistency of the loops. The post-elastic performance of the tested specimen arises from the exploitation of



(a) (b)

Figure 2: (a) Photographic image of the specimen as in the experimental setup. (b) 3D view of the base-plate assembly.

the dissipative failure mechanism (Type 1 mechanism [12]), which can be promoted by design guaranteeing strong-bolt weak-flange resistance relationship. It is characterized by the formation of a plastic hinge in the T-stub flanges, plus a circular pattern around the bolt's axis (ref. Fig. 4).

As it can be noticed, the shape of the cycles can be related to similar experimental results, in which the performance of T-stub connections was studied, accounting for energy dissipation capacity and stiffness degradation for the pinching of the hysteresis loops [18].

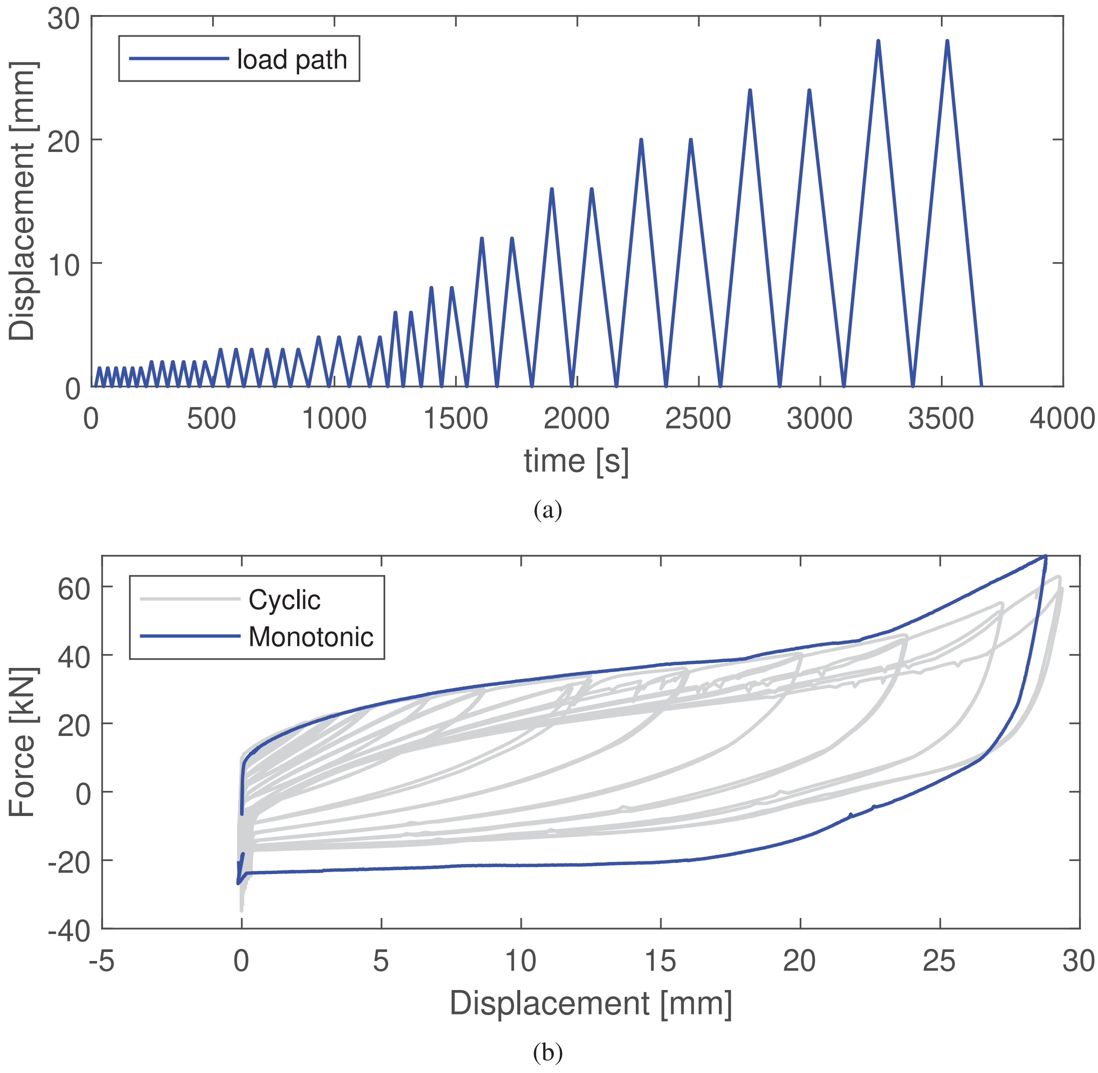


Figure 3: (a) Cyclic loading protocol and (b) experimental results of the tests.

3 NUMERICAL MODELLING

As the finite element (FE) method is widely employed as an approach to develop numerical prediction models, many researchers have been using it to support their investigation [19, 20, 21]. In this study, the COMSOL software has been used. The Johnson-Cook hardening law was used to model the strain rate dependency of the plastic hardening; the material properties are presented in Section 2.1 of this study. The 3D FE model geometry reproduced the half geometry of the experiments, using symmetric conditions in order to minimize the computation effort. As well as the simulation used similar boundary conditions and loading as in the experimental

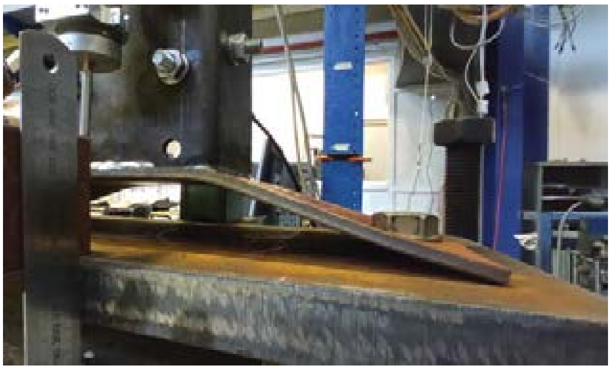
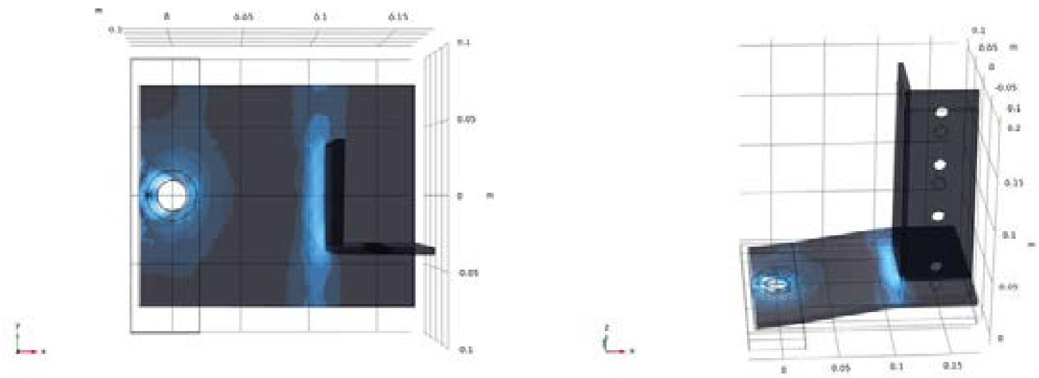


Figure 4: Lateral view of the specimen at the end of the monotonic test

program. A sensitivity analysis was conducted to identify the best meshing and, in total, 79759 elements were used (4-nodes solid elements). Contact conditions between two surfaces are governed by kinematic constraints in the normal and tangential directions. The normal stress at contact is either zero when there is a gap between the two surfaces, or compressive when the surfaces are in contact. The contacts are defined in the augmented Lagrangian method with the penalty factor controls. In addition, material and geometric nonlinearities have been taken into account. The nonlinear solver uses an affine invariant form of the damped Newton method. In this section, static analyses have been performed with increasing displacement, in the same fashion of the experimental test. The numerical results were compared with the experimental ones and the validation of the model was based on: (i) the force-displacement curves, and (ii) the deformation shape of the specimen (Figure 5).



(a) (b)

Figure 5: Top (a) and 3D (b) view of the specimen at the end of the monotonic test; the right hand side picture highlights the plastic hinge in correspondence of the T-stub web and a circular pattern around the bolt.

4 CONCLUSIONS AND FUTURE RESEARCH NEEDS

This work explores the performance of a T-stub-like connection that can be used to improve the seismic performance of pallet racking systems, with the aim of increasing the energy dissipation capacity of the upright frames. The sample was shown to have similar performance to a standard T-stub, which is widely used to model the overall 3D behaviour of beam-to-column connections of steel structures. This type of connection can be used for the construction of new lateral resisting structures, as well as for the retrofitting of existing ones, where lateral loads are a problem.

5 ACKNOWLEDGEMENTS

The first author's Ph.D. scolarship is granted by the Italian Ministry for Education, University and Research (MIUR) as part of the program "Dottorati Innovativi a caratterizzazione industriale", ID DOT 1328490–3, funded by the European Union (Structural Funding ERDF-ESF for "Research and Innovation" 2014-2020). The authors are grateful for the support.

Parts of the test set-up were delivered gratis by J Dimitriou Ltd Kataskevastiki. This support is acknowledged.

Part of the material used for the testing campaign was provided by NEDCON B.V. (The Netherlands). The authors would like to express their very great appreciation to Ir. Jan Hermanek.

6 CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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