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Behavior of steel storage pallet racking connection - A review

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Abstract. Steel pallet racking industry has globally used from the industrial revolution and has deeply evolved from hot-rolled profile into cold-formed profile to raise the optimization in engineering field. Nowadays, some studies regarding cold-formed steel profile have been performed, but fewer studies in terms of cold-formed pallet racking specifically in connection due to the semi-rigid behavior by lug-hooked into the upright have been conducted. The objective of this study is to review the related literature on steel storage racking connection behavior.

Keywords: steel pallet racks; beam to column connection; cantilever testing; moment resistance; stiffness; ductility

1. Introduction

Constructions have played a significant role in infrastructures and shape the environment people live in. A growing demand on the structure and infrastructure adapted to an ever-changing social landscape has mainly raised the novelty of engineering materials (Mohammadhassani *et al*. 2013, 2014b, Arabali *et al*. 2016, Freeman *et al*. 2016, Mansouri *et al*. 2016, Hosseinpour *et al*. 2018, Mehrmashhadi *et al*. 2018, Nasrollahi *et al*. 2018, Sadeghipour Chahnasir *et al*. 2018, Shahnazar *et al*. 2018, Toghroli *et al*. 2018b, Zandi *et al*. 2018, Zhao *et al*. 2018a). It also bring solutions to guarantee the optimum exploitation of resources, and foster more sustainable use of assets (Gerami *et al*. 2008, Gholhaki *et al*. 2008, Haddad 2008, Kheyroddin *et al*. 2008, Sharbatdar *et al*. 2008, Andalib *et al*. 2018, Bazzaz *et al*. 2018, Paknahad *et al*. 2018), therefore, majority of studies have been conducted to determine the preference for familiarity or preference for novelty of structures (Ardalan *et al*. 2009, Mohammadhassani *et al*. 2013, 2014a, b, Mola-Abasi *et al*. 2013, Eslami *et al*. 2014, Toghroli *et al*. 2014, Safa *et al*. 2016, Shahabi *et al*. 2016, Sedghi *et al*. 2018, Toghroli *et al*. 2018a). Accordingly, few studies are on the cold-form beam-to-column connections (Mohammadhassani *et al*. 2012, Sohel *et al*. 2012, Talaiekhozani *et al*. 2014, Zhao *et al*. 2014, El Kadi and Kiymaz 2015, Shah *et al*. 2015, Bao *et al*. 2016, Shah *et al*. 2016a, b, c, Bertocci *et al*. 2017, El Kadi *et al*. 2017, Haji Agha Mohammad Zarbaf *et al*. 2017a, Li *et al*. 2017, Sarangapani and Ganguli 2017, Zhao *et al*. 2017, Dai *et al*. 2018, Shariati *et al*. 2018), while few others are on the connections of C-Channel profile with bolted condition. The number of studies on cold-form profile for steel pallet racking connection with lugged (Fig. 1) and bolt - nut condition (connect upright with beam end connector through bolt-nut) have been rarely performed.

2. Cold formed steel structure

2.1 General

Cold-form steel structure has been formed in a desired shape in ambient temperature when carrying a wide

Fig. 1 Lug connection of steel pallet racking

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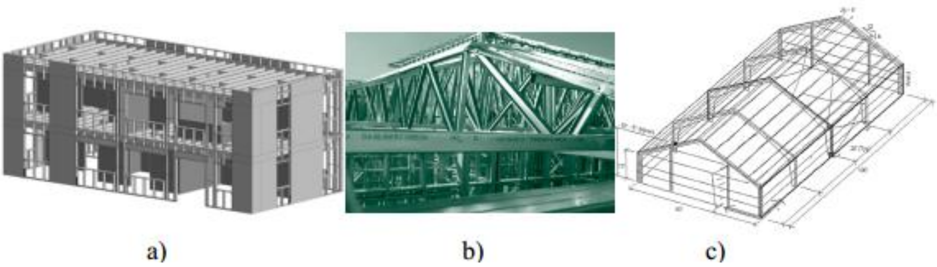

Fig. 2 Cold-form structure application in steel building

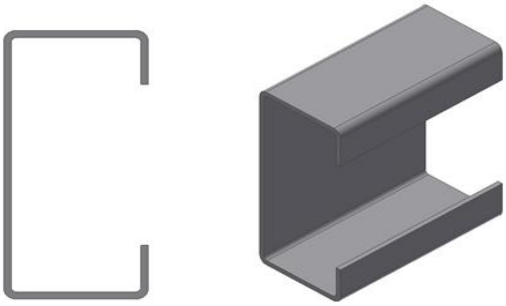

Fig. 3 C-shape lipped channel

industrial application mainly in construction, automation, and steel products. The excessive application of cold-form steel is due to its relative light weight and flexibility of the designing contributed to the cost effective. Several main advantages of cold-form steel structure are listed below:

- Light in weight
- Yield strength increase after formed the profile
- High ductility
- Ease of manufacturing
- Low cost

The studies of cold-form steel beam column application has been performed by (Shifferaw 2012) and also focused on trusses and load bearing framing, commonly used in residential and commercial mid-rise cold-form steel building (Fig. 2), The study has investigated the efficiency of the industrial section led to the wide use of C-Shape lipped channel (Fig. 3) as the most popular section due to its simplicity in manufacturing as well as global marketing availability.

2.2 Beam design criteria for beam structure

Prior to discussing the failure behavior of the beam structure, beam design has included the criteria based on the standards EN15512:2009 as follows:

(a) Deflection

In case of too much deflection, steel pallet beam has become unserviceable. The deflection of beam is mostly governed by the pallet load on top of the beam and length of the pallet beam following the standard of each country, say European Standard, EN15512:2009 Section 11.2 uses the span/200 as the deflection limit, however, AS4084:2012 from Australia uses the span/180 as deflection limit.

(b) Connection - Bending Moment (Moment Resistance)

The bending moment for the pallet beam is defined by few variables listed below:

(i) Unit Load weight
(ii) Center of Gravity of the unit load on the pallet
(iii) Seismic action resulted by the horizontal forces of seismic action

Typically, structural engineering has analyzed the bending moments of beam (in the structure) by second-order analysis at design load factor. The bending moment values are normally defined from the testing or from finite element (FE) analysis / testing.

(c) Lateral Torsional Buckling of Beam

Lateral-torsional buckling of beam is defined as the deformation of a beam by lateral deflection from the initial position combined with twisting prior to drop off due to large deflections of the beam (Kumar 2013).

(d) Material Stress Capacity

The design of stress limit has not exceeded the yield point of the material itself.

(e) Shear Capacity of the connection

The design of the connection has considered shear capacity of the connection. Generally, the design of shear has been confined by longer length of beam and the shear capacity has been turned out to be non-critical, however, the moment resistance of the connection should be precisely designed.

In designing a beam to column connection, few crucial parameters have been regarded; say the cost efficiency of beam design allowing the acceptance of design in industry, respectively, manufacturing process and time requirements of connection installation are also important requirement to be considered.

2.3 Connections

In structure steel, there are 3 basic connections (McGuire 1995) classified as:

(i) Pinned (Hinge) Connection
(ii) Fixed (Rigid) Connection
(iii) Semi-Rigid Connection

Semi-rigid connection (McGuire 1995) has been established between the pinned and fixed connection, but

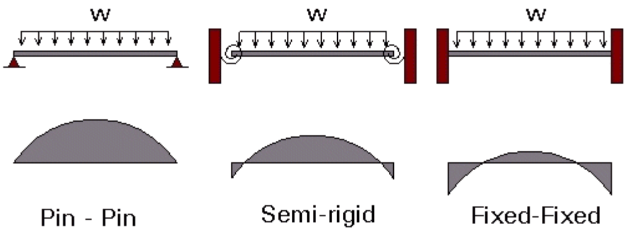

Fig. 4 Moment diagram of pin, semi-rigid and fixed connection

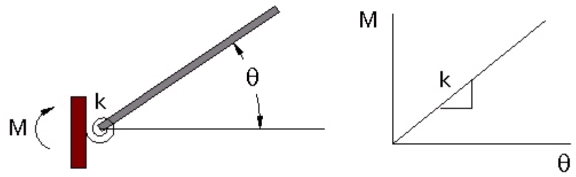

Fig. 5 Relationship of the stiffness in moment-rotational diagram

without losing the flexibility of the hinge connection. Therefore, it has partial capacity like rigid connection to resist the forces. Semi-rigid connection is also named "flexible connection" (McGuire 1995). According to Figure 4, semi-rigid moment has transferred moments to do support by establishing the stiffness on the connection, where the stiffness (rotational rigidity) is the rotational spring represented by the moment-rotation behaviors of the structure (Fig. 5).

A semi-rigid (partial strength moment) connection has possessed some degree of rotational stiffness and moment capacity, however, is inadequately stiff to evolve full continuity and unable to attain full moment capacity of the members at a joint.

2.4 Ductility

In a common steel material to consider as ductile material, EN1993-1-1(Standardization) 2005) has stated the requirement of the steel as follows:

(i) Ratio $F_u/F_y > 1.10$
(ii) Elongation at Failure >15%, and
(iii) $\varepsilon_u \geq 15\varepsilon_y$

F_u = Tensile stress of material
F_y = Yeild stress of material
ε_u = Ultimate strain of material
ε_y = Ultimate strain of material

Consequently, ductility is the capability of deformation in plastic region prior to fully delocalize of materials. In a moment connection, ductility behavior of the connection joint is measured with rotational capacity. Partial strength joint also has referred to "Ductile Connection", while the partial strength joint is defined as none-rigid joint. Several ductility of joint in structural frame has been classified in Table 1:

A novel method to evaluate ductility and rotational stiffness of these connections to perform a plastic design for both seismic and service loading has proposed (Faggiano *et al*. 2009).

Table 1 Ductility class of structural behavior (Grecea *et al*. 2004)

Structural behaviour	Ductility class	Range of ductility factor
Low dissipative	Low	≤ 1.5 - 2
Medium dissipative	Medium	≤ 4
High dissipative	High	≈ 4 (Limits by the EN1998-1)

3. Research on steel rack structure

3.1 Research on cold-formed steel structure beam to column connection

An experimental investigation to evaluate the structural performance and suitability of few bolted moment connections between cold-form beam to column as partial strength connection in terms of practical application has performed (Ahamed and Mahendran 2010).

The proposed connection configuration of cold-form steel structure beam to column connection has been represented in Fig. 6, also tested by various configurations of beam heights of 150 mm, 200 mm and 250 mm, which the column has been maintained at 250 mm width sections. Several useful connection characteristic has presented (Ahamed and Mahendran 2010)

(i) The moment resistance and the stiffness of the connection have been increased when the height of beam is increased.
(ii) Connection type T4 has gained the highest moment resistance among the 4 connection types. Accordingly, the connection moment resistance has been decreased in T2, T3 and T1 sequences. By increasing the bolt - connection, the moment resistance of connection has been also increased.

Increasing of beam depth has not significantly affected the ductility of the connection, in which the ductility of the connection has been influenced by the connection type.

Another experimental studies to evaluate the flexural behavior of beam to upright bolted connections in cold-form steel storage racks has performed (Dai *et al*. 2018). A monotonic loading on 21 specimens in various thickness, height and tabs have been applied. The connections have been leveled in semi-rigid and partial-strength with almost ductile failure modes, respectively; a cantilever setup for the experiments has been used followed by the results:

(1) The connection failures are classified as Beam End failure, Tab crack and Tearing or buckling the up-right.
(2) Upright Thickness, Beam height and the number of tabs are the most pivotal geometric factors directly affected the flexural behavior.

Bolted connections have a favorable ductility and strength compared to boltless connections.

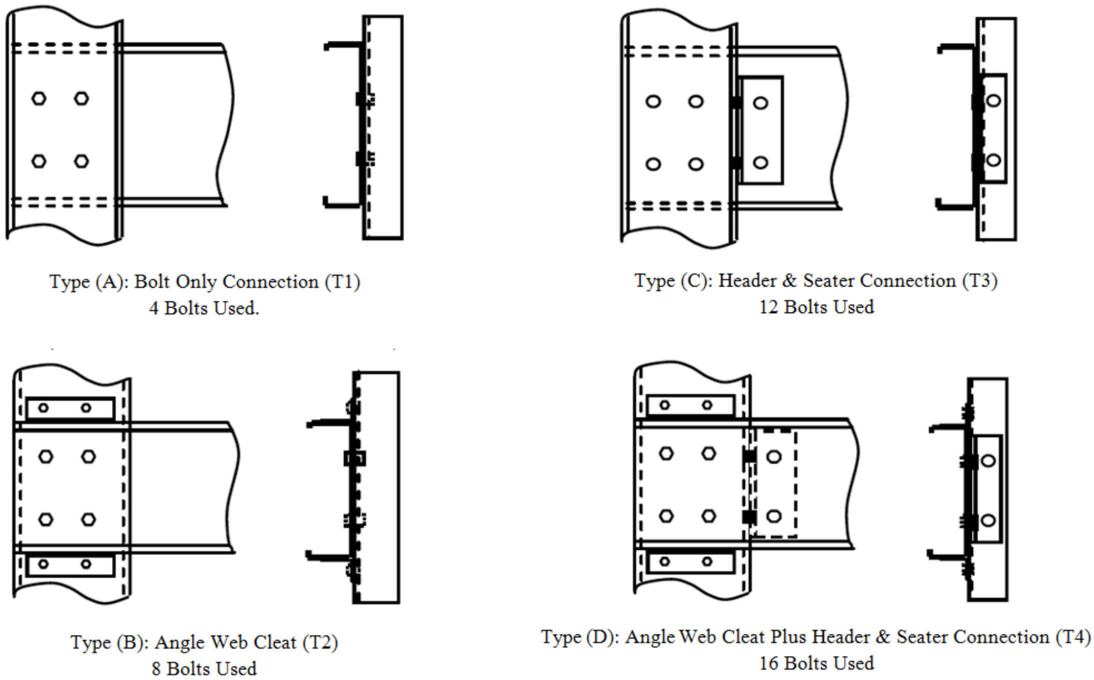

Fig. 6 Connection configuration of cold-formed steel structure beam to column connection by Ahamed and Mahendran (2010)

3.2 Research on steel storage rack beam-column connection

The experimental tests to define the characteristic of diverse connections for steel storage racking has conducted (Markazi *et al*. 1997). Indeed, there is few commercial design of racking connection classified as Class (A): Tongue and slot design (Fig. 7), Class (B): Blanking Design (Fig. 8) and Class(C): Stud-Incorporate design (Fig. 9), The purpose of studies performed by (F.D. Markazi 1997) is to determine the variable governing the efficiency of beam end connection.

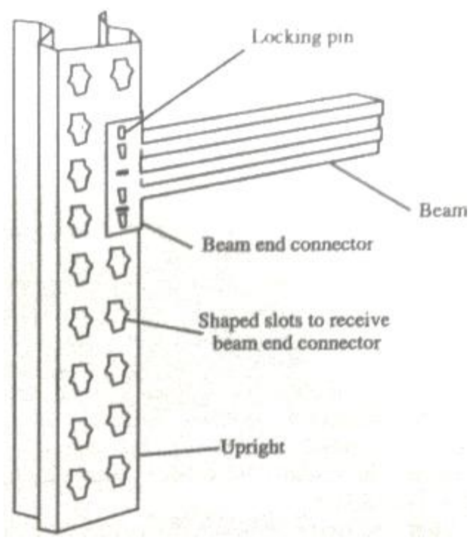

Fig. 7 Class (A): Tongue and slot design (Markazi *et al*. 1997)

A test for all connector classes with various parameter-design like beam size, welding position of beam to connector, and various height of beam end connector to beam height has been conducted (Markazi *et al*. 1997). After doing a serial tests, (Markazi *et al*. 1997) has been concluded the factors affecting efficiency of the beam end connector design as follows (Markazi *et al*. 1997):

The quantity of the connector-hook. While the amount of connector is increasing, the stiffness and moment resistance has been also increased to possess the location of hooks that must be arranged in the position to resist the apply loads.

(i) The geometry detail of the connector-hook. The resistances of the moment have created a concentrated load in plane of connect to the

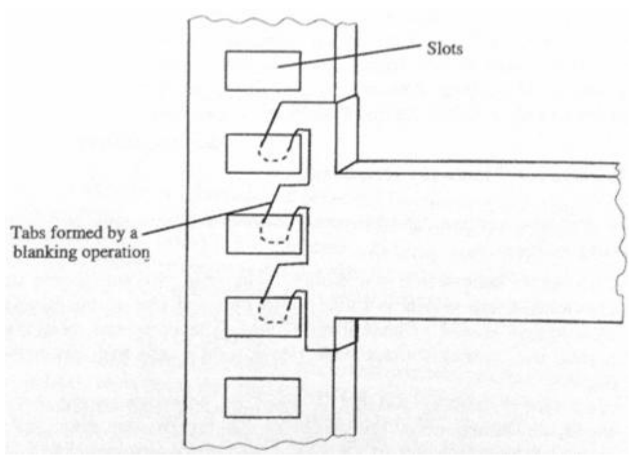

Fig. 8 Class (B): Blanking design (Markazi *et al*. 1997)

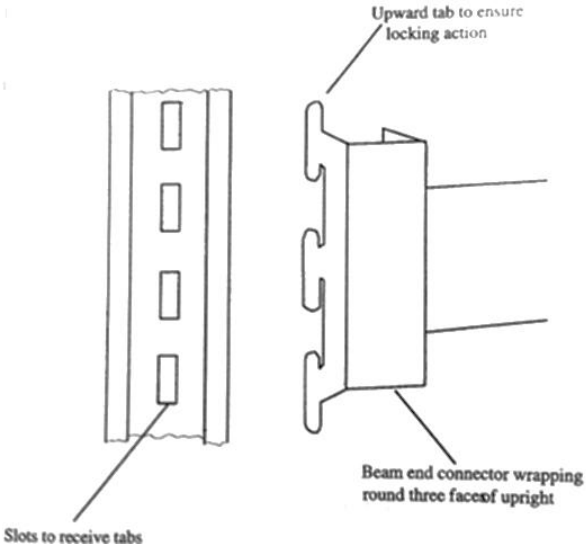

Fig. 9 Class(C): Stud-incorporate design (Markazi *et al*. 1997)

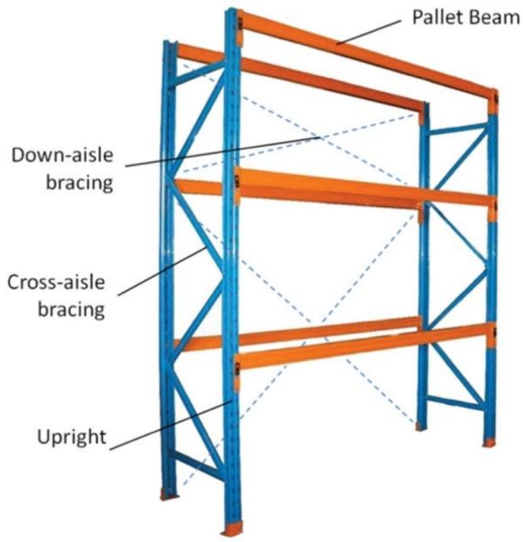

Fig. 10 Typical rack frame

upright. The fine design has possessed a capability to absorb (distribute) the stress.

(ii) Design of the bracket (Connection holes on the upright), The design of the connected holes to the upright is the critical influence of the stress concentration.

(iii) Gauge of the beam end connector and the upright. The increase of gauges has increased the stiffness.

(iv) The profile of the upright. The greater profile of the upright has increased the stiffness.

A shell element-based finite element analysis on the steel storage rack frames showing that the current component experiments for rack frame-connections have overestimated the joint's flexibility, while they are inefficient to remade the actual behavior of the connection at system level has provided (Cardoso and Rasmussen 2016) (Figs. 10-13).

The ultra-light gauge steel storage rack frames has been investigated (Trouncer and Rasmussen 2016) and the results have indicated that a member rigidity reduction occurred by local instability has not been counted in GNA analyzing, accordingly, the design loads have become less conservative when the uprights' slenderness has been raised. The outcome has also shown that the design loads has become unsafe when the uprights' slenderness (λs) has been increased 1.2. In a section slenderness of 2, the GNA-based design loads are optimistically around 10%. This study has provided some investigation for a proper reduction factors used to uprights based on GNA analysis. On the other hand, the study has also discussed the methods to account another second order impacts provided for cross-sectional buckling deformation by decreasing the members' flexural rigidity when the local or distortional buckling load has been raised.

The steel storage racks compressive strength under applied axial forces has been studied (Elias *et al*. 2018). Compared to numerical analysis, the results have shown the failure mode of global buckling as flexural and torsional. The final loads gained from the proposed buckling curve are less conservative than DSM equations.

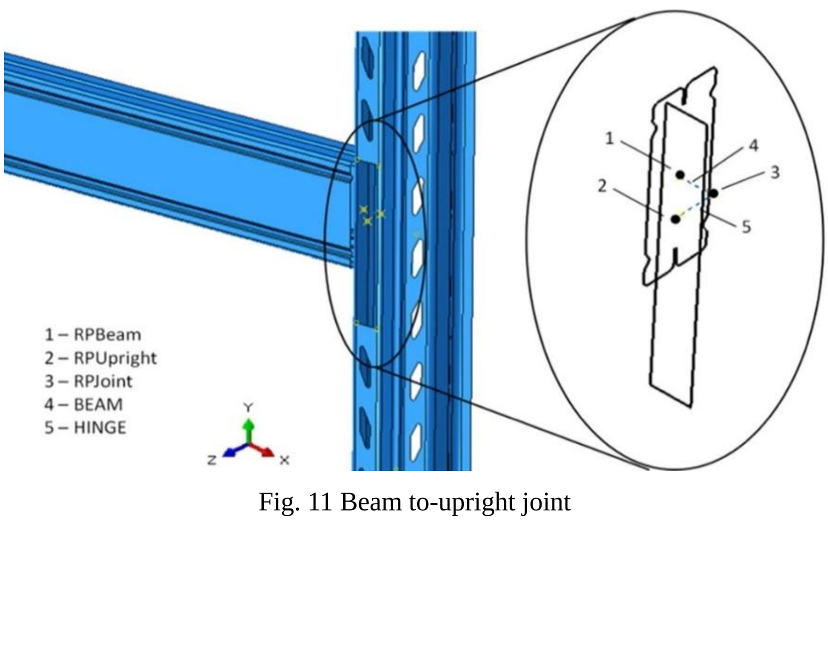

Fig. 11 Beam to-upright joint

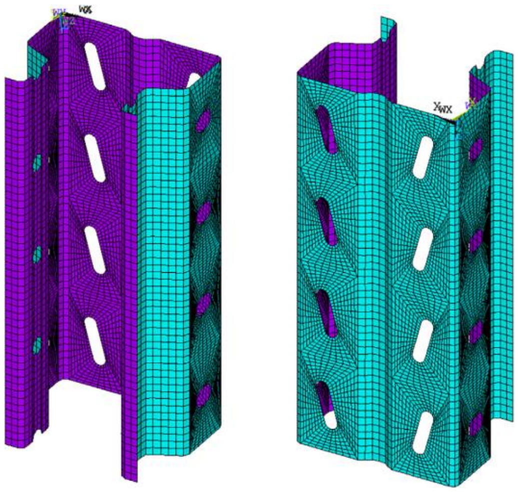

Fig. 12 Mesh used in ANSYS0

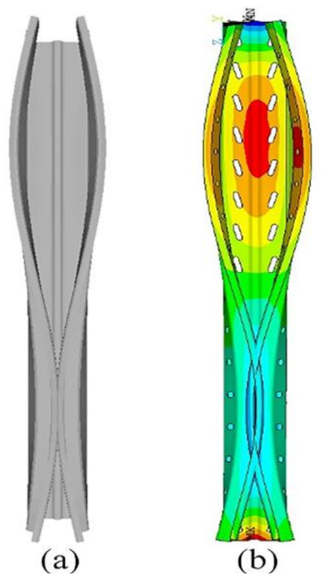

Fig. 13 Critical buckling modes

3.3 Research on steel storage racking connection behavior during seismic event

The possible damages of earthquake action has been introduced (Uma and Beattie 2011). To resist the seismic action, two main connections in the racking structure are defined:

(i) Beam to column connection (down-aisle direction)
(ii) Bracing frame (cross-aisle direction)

During the seismic event, the down-aisle direction of the beam to column connection has been exerted the plumb deflection in the form of "bow" (Uma and Beattie 2011). The out-of-plumb action (Fig. 14) has been caused by the moving of floor due to the seismic action, however, the racking structure is fixed on the floor by the base plate.

In down-aisle direction, the common damage presented by Uma and Beattie (2011) is the failure mood of the beam connector element. The connector is the component of beam transferring the beam moment. During the seismic event, the connector has formed the distress by the material crack, fracture or weld cracks. The losses of the connector-strength have reduced the resisting strength of the connection, highly causing the failure of the overall structure.

The stability of steel storage rack connections through Lewis, considering the nonlinearity of structure by incorporating the stiffness effect of connections has been studied (Firouzianhaji *et al*. 2014). Moreover, the stability analysis proposed by (Lewis 1991) has been improved to consider dual storage rack systems incorporating spine bracing and base plates.

The seismic response of cold formed steel storage racks with spine bracings by applying 2 connection type through the Incremental Dynamic Analysis (IDA) has been investigated (Yin *et al*. 2018). The connection behaviors of structural model have been maintained according to the series of connection tests. According to IDA and the associated fractile curves, all racking have proved a soft behavior because of the dynamic instability, subsequently, the study of the dynamic response has shown the location of higher inter-story drift angle localized at the first or second story based on the rack. The collapse mechanism of two racks has been carried out the same outcome derived from the pushover analyzing. While DEU (dual entry unit) rack using JD1 connection has shown a raising in base shear compared to SEU (single entry unit), JD5 usage has obviously declined the base shear.

Several different steel storage racks with a variety of geometric layout and component performance to achieve a reasonable seismic criteria and behavior of the connections in seismic zones has been studied (Bernuzzi and Simoncelli 2017). Besides, in a case study by (Bernuzzi and Simoncelli 2016), the steel storage racks by combining nonlinear time

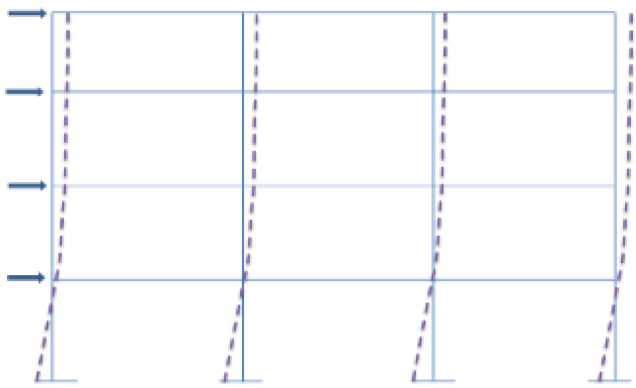

Fig. 14 Out-of-plumb action with "bow" effect on upright members (Uma and Beattie 2011)

Table 2 Calibrating parameters

	Ko	Fo	Kd
JD1	88.13	17.77	−168.34
	84.13	-17.42	179.46
JD5	87.25	30.20	−174.79
	61.67	29.36	160.04

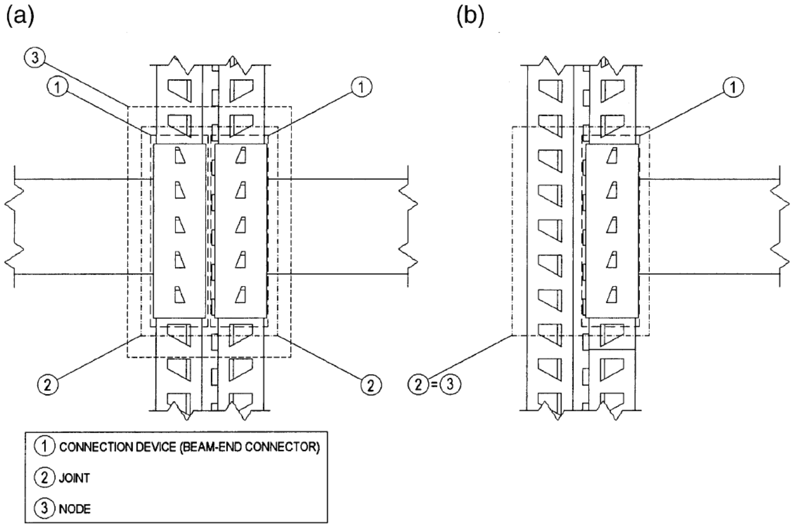

Fig. 15 Definition of node and joint (Bernuzzi and Castiglioni 2001)

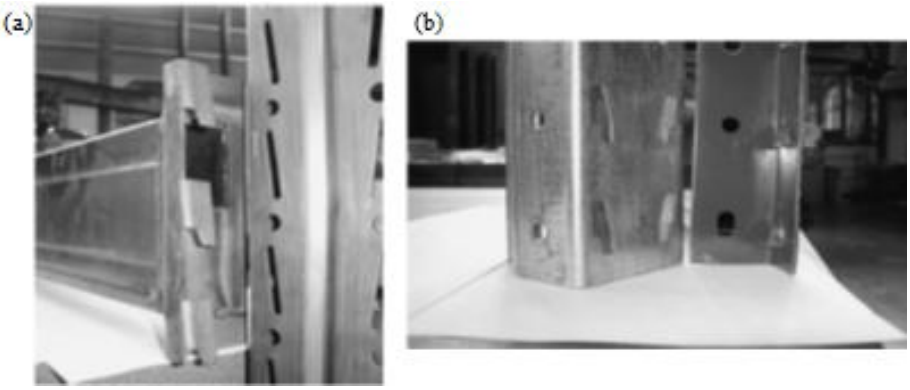

Fig. 16 Components of the tested joint specimens: (a) type A; and (b) type B node (Bernuzzi and Castiglioni 2001)

history approach and low cycle fatigue method has been studied to evaluate the damage distributions, assess the residual fatigue life and forecast the load carrying capacity after Earthquake.

3.4 Research on steel storage pallet racking cyclic behavior of beam to column connection

The experimental analyzing to define the cyclic behavior of beam-column connection in steel storage pallet racks has been used (Bernuzzi and Castiglioni 2001). In their research, seismic design of steel storage pallet rack would be proposed by capacity design approach providing the structural systems with adequate strength, stiffness and absorption potential to dissipate the energy of strong earthquakes through the "plastic" mechanisms in dissipative zones, accordingly, the frame collapse is typically occurred because of the interaction between instability and plasticity of beam-column joints when the column has never achieved ultimate strength; However, in few conditions, a plastic hinge has been located almost at the beam mid-span. To assume dissipative zones located at the nodes between beam (s) and a column has been reasonably regarded or the capability to dissipate energy of the rack systems has been also regarded based on their hysteretic behavior, say the response to cyclic reversal load. Consequently, despite the lack of test data, an important effect of beam-column joints has been seen in the response of the rack frame in the presence of seismic load.

Their study has also drawn a clear picture of node and joint in which a node is a point that the axes of two or more interconnected structural elements have been converged and a nodal zone is defined, if an interaction between these members occurs. The node and joint of the storage rack graphically is shown in Fig. 15. Two type of connecting device are used to conduct and compare the behavior (Fig. 16), The experiment yields the results and present graphically in Figs. 17 and 18:

According to the experiments, the steel storage pallet racking cyclic behavior of beam-column connection has comprised the following parameters:

- The initial cycle is stable and regular followed by the progressive and regular deterioration of stiffness. The reloading/ unloading branches of initial cycle in plastic range are close to the responses derived from monotonic tests.
- In the next cycle, the form of the hysteresis loops has

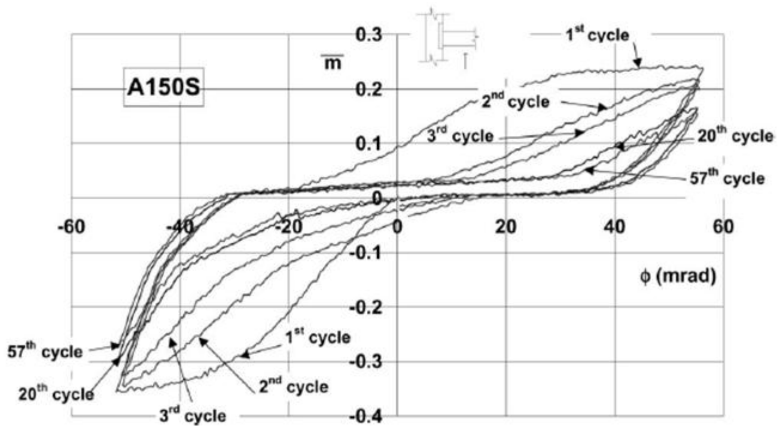

Fig. 17 Moment–rotation joint curve for A150S joint specimen (Bernuzzi and Castiglioni 2001)

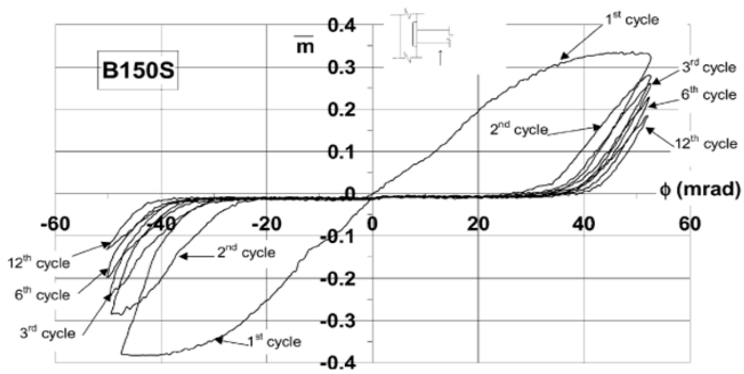

Fig. 18 Moment–rotation joint curve for B150S joint specimen (Bernuzzi and Castiglioni 2001)

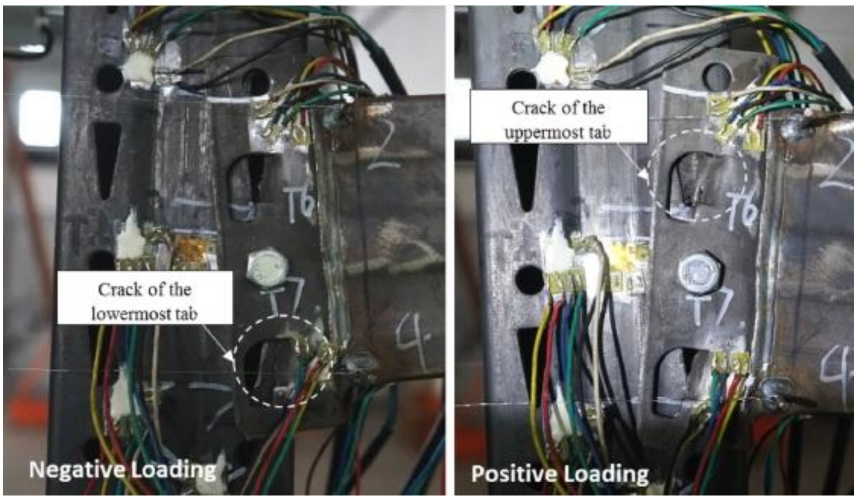

Fig. 19 Tab crack

been literally changed via the residual deformations' affection of the connection device. Particularly, by raising the number of cycles, the form of the hysteresis loops has basically depended on the connector types. In A joints, the moment-rotation curve has been characterized by the loops, in which the reloading branches' stiffness has been declined steadily align with the test. In B joints, the subsequent cycles caused by the first branch in a modest slope, the related extension has been increased by the cycles' number. The reloading phases' stiffness is actually stable and equal to the stiffness of the first cycle and monotonic tests.

- Considering the increment of the performed cycles in the tab and column zone of the slot vicinity, cracks have been occurred and their amplitude is raised align with the test. The dissipation of energy has significantly been decreased by the raising of the

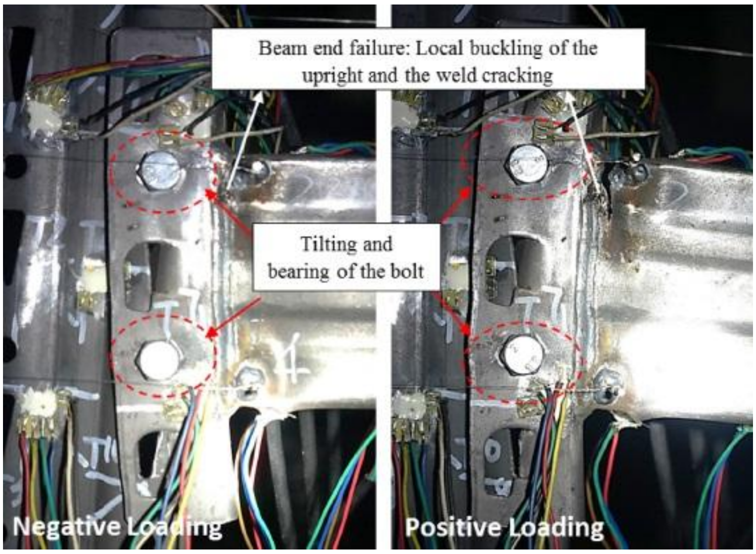

Fig. 20 Beam end failure

cycles' number. In the second cycle, mean decrement (30% and 61%) has been seen for A and B joints.

To sum up, the connection performance is a significant parameter on the whole frame response. The slip with plastic deformation across an earthquake has caused huge sways in the column, increasing the second order effects and signifying the proper design for pallet racks in seismic zones. Accordingly, the strength degradation and the potential of energy dissipation beside the crucial impact of connection devices as hysteresis loops have required variable amplitude tests.

The cyclic behavior of steel storage rack beam to upright bolted connection has studied (Zhao *et al*. 2018b) in which three basic failure modes have been observed as tab crack (Fig. 19), local buckling of upright and beam end failure, therefore, the positive moment-resistance has monotonically been progressed by raising of upright thickness, beam height and tabs number (Fig. 20).

The cyclic behavior of cyclic response of speed lock connections with bolt and weld in storage rack has been investigated (Yin *et al*. 2016), besides the study of cantilever setup to use the requisite cyclic loads through the use of five separate specimens: (1) common speed-lock connections; (2) speed-lock connections with upper bolts (3) speed-lock connections with lower bolts (4) speed-lock connections with two bolts; and (5) speed-lock connections with two bolts and welded all around. The outcome has indicated that by increasing of the blots (welds), the energy dissipation and bearing capacity of the connections has also increased, besides a slight change in initial stiffness or equivalent stiffness.

The seismic behaviors of steel storage racking in a real-scale view with the failure mechanisms have been studied by (Kanyilmaz *et al*. 2016) (Fig. 21), Subsequently, avoiding a global brittle collapse occurred by sudden failure of spine bracing rack connections has required adequate over- strength for bracing connections such as bolt shear and bolt bending failure. Furthermore, adequate space between bolt and edge of bracing should be designed to avoid bolt bearing, also to keep the strength of bolt at least 20% more than the bearing strength in conjunction with the general rule for bolted connections (Fig. 21).

A cyclic test on beam to column steel racks to evaluate the optimal welding length and to investigate failure modes by replacing fasteners instead of welding in some cases have been conducted by (Gusella *et al*. 2018). According to the results, the cyclic tests of beam end joints have needed to assess the reliability of the real behavior beside a seismic vulnerability analyzing of pallet rack. Therefore, using more bolts has represented an effectual solving to surpass the seismic response of steel storage pallet racks in a

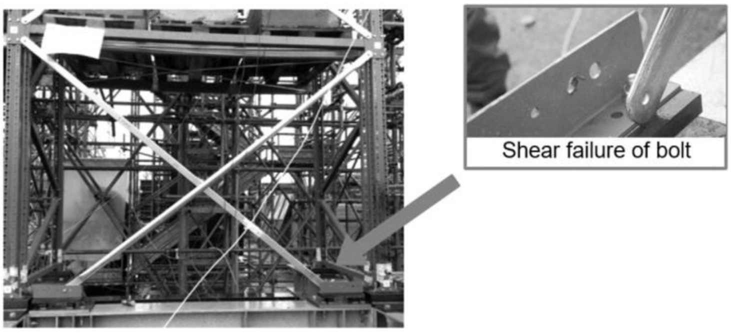

Fig. 21 Shear failure of bolt

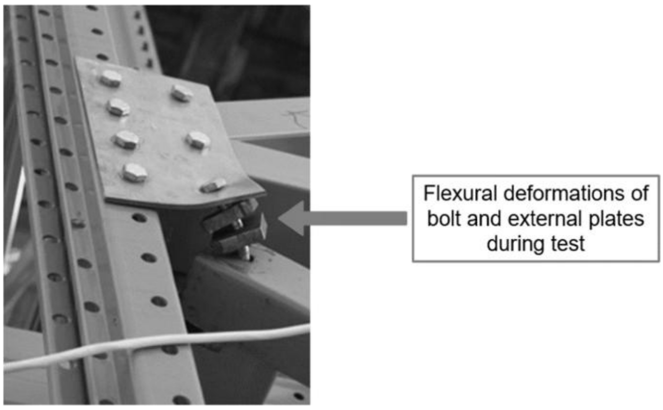

Fig. 22 Connection failure mechanism

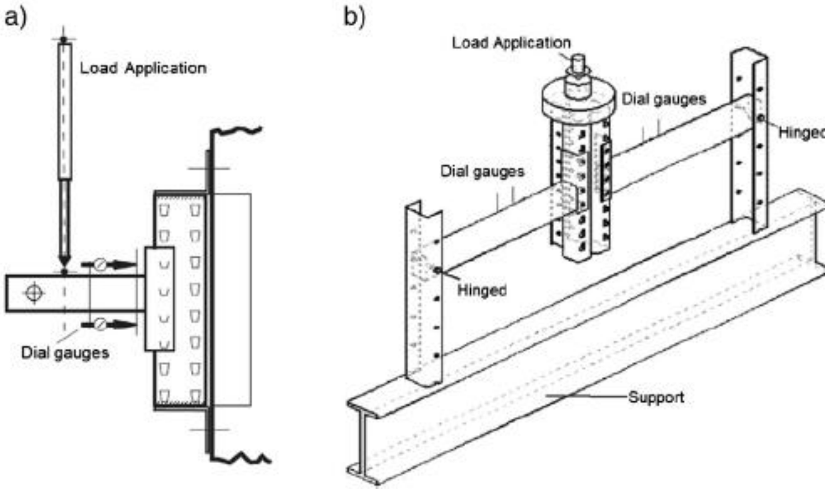

Fig. 23 Beam end connector test setup type (Zhao *et al*. 2014)

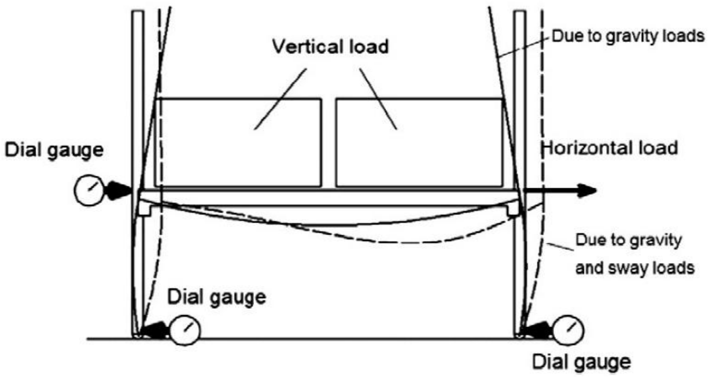

Fig. 24 Portal frame setup test for beam end connector test (Zhao *et al*. 2014)

seismic vulnerability analysis.

3.5 Research on experimental method to conduct experimental investigation

The flexural behavior of steel storage rack beam to upright connection, comprising two approaches as cantilever test and portal frame test has studied (Zhao *et al*. 2014).

The cantilever test, comprising all its 3 features except few in test dimensions and procedures (Fig. 23(a)), has widely been conducted to study the rotational behavior of beam to upright connections of storage rack in monotonic (cyclic) loading. During the test, the connection has been loaded to failure mood providing the design of storage rack members and their connections. In the following, a double cantilever test setup (Fig. 23(b)) in which the end connectors have provided 3 types of forces as: (1) moment;

Fig. 25 A typical mono-symmetric upright section

(2) shear; and (3) axial pull representing the real field condition have been performed (Bajoria and Talikoti 2006). Indeed, double cantilever test has produced the shear to moment ratio in a real rack frames. On the other hand, the connections of both ends of setup in a double cantilever test have not probably been loaded or deformed, specifically in nonlinear range that might obtain erroneous moment rotation features to the connections**.** The portal frame test (Fig. 24) is based on the Australian Standard AS 4084 but not European Standard EN 15512:2009. Since the portal frame test is able to define the connections' average stiffness but not the behavior of two connections on both sides of the portal frame, then test wouldn't establish the exact connection behavior.

4. Novel sections of steel storage racks

The design of new non-symmetric sections by finite element model has studied (Bernuzzi and Simoncelli 2016) reporting that a safe and optimal design has been attained if the cross sectional warping has adequately been accounted in structural analysis. Considering the pallet beams, the errors related to the adoption of design procedure neglecting the key parameters of non-bi-symmetric cross sectional members are definitely non-negligible, and obviously greater than the ones discussed with reference to the uprights of selective pallet racks. Meanwhile the design approaches admitted for steel racks based on EU and US steel design provision, evaluating the warping effect in racks with mono-symmetric uprights have also been compared by Baldassino *et al*. (2019) (Fig. 24).

5. Conclusions

In this study a comprehensive literature on behavior of steel storage racking connection is reported. Research on cold-formed steel structure beam to column connection, steel storage rack beam-column connection and their behavior during seismic event and cyclic behavior have been covered. The particulars of all the researches' results in this area are covered and described in details. It is concluded from experimental tests that the outcomes of portal frame test are generally appropriate for sway analyzing in the gravity loaded rack structures. The values of cantilever test based connection stiffness are generally half of the values in the portal frame based test. When the portal beam is a gravity loaded with the service pallet load, both connectors (left and right) are adjusted to closing up-moments, in which the beam ends are perpendicular to the upright and begins to rotate to the upright. Later, if the portal frame has been subjected to a horizontal load, one connector has experienced a growing moment, and however, the other one has experienced declined moments. Therefore, one end has experienced an increasing closing up, while the other connector has started opening or unloading. Consequently, unloading stiffness is obviously greater than the loading stiffness, resulted in two various stiffness values for the connectors (right/left), also the cantilever test is highly favorable to attain the moment-rotation behavior of beam to upright connection of steel-storage pallet rack. At the end, novel sections of steel storage racks were presented.

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