University of Technology, Sydney
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# The Effect of Connection Flexibility on the Seismic Performance of Industrial Racking Systems

**by**

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**PhD Thesis**

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student:

Date: 11 Jun 2015

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# NOTATION

The following symbols are used through the thesis unless notified otherwise:

| | |
|---|---|
| $A_{brace}$ | Cross section area of bracing members |
| $A^{*}_{bracing\ member}$ | Modified cross section area of the bracing member |
| $A_{bracing\ member}$ | Cross section area of the bracing member |
| $A_d$ | Cross sectional area of the bracing members |
| $C$ | Damping matrix, or; |
| | Number of storey levels |
| $D$ | Upright width, or; |
| | Nominal diameter of bolt |
| $D_{EqCyc}$ | First yield rotation on the moment-rotation backbone |
| $E$ | Elasticity modulus |
| $F_1$ | Vertical force applied by Jack 1 |
| $F_2$ | Horizontal force at pin above upright |
| | The calculated frequencies at a response amplitude of |
| $f_a, f_b$ | '$^1/_{\sqrt{2}}$' of the peak response amplitude |
| $f_b(\theta)$ | Moment rotation function of base plate connections |
| $f_c(\theta)$ | Moment rotation function of beam to upright connections |
| $f_n$ | Forcing frequency at resonance and |
| $f_o$ | First yield force in the push over curve |
| $F_{ult}$ | Upright – hook interaction |
| $f_y$ | The force at which the structure starts to yield (yield strength) |
| $H$ | Beam spacing , or; |
| | Storey height |
| $I$ | Second moment of inertia of the upright member about an axis perpendicular to the upright frame |
| $I_b$ | Second moment of area of the beam, or; |
| | Moment of inertia of bolt section |

| | |
|---|---|
| $K$ | Stiffness matrix, or; |
| | Stiffness of a SDOF system |
| $k$ | A factor depending on the position of the loads |
| $k_{1YEqCyc\ Initial}$ | Stiffness of the equivalent moment rotation backbone |
| $K_{avg}$ | Average stiffness of the moment rotation curve |
| $K_{bearing}$ | Bearing stiffness |
| $K_{bolt}$ | Stiffness of the bolts in the bracing connection |
| $K_i$ | Initial Stiffness |
| $K_{joint}$ | Stiffness of the bracing connection in vertical direction |
| $K'_{joint}$ | The joint stiffness in the direction of the bracing member |
| $K_{member}$ | Stiffness of the bracing member |
| $K^*_{member}$ | Equivalent stiffness of the bracing members |
| $K_s$ | Initial secant stiffness |
| $K_{shear}$ | Stiffness of the shear frame excluding base plates |
| $K_{shear\ total}$ | Stiffness of the shear frame including base plates |
| $K_{uplift}$ | Stiffness of the base plate connection under uplift forces |
| $L$ | Vertical distance from the load point to the connector's free edge, or; |
| | Distance between pin above upright and bottom of the base plate, or; |
| | The total height of the upright frame |
| $L_b$ | Distance between upright flanges, or; |
| | Length of the beam |
| | Total mass of a SDOF system, or; |
| | Moment in the beam to upright connection |
| $\overline{m}$ | Non-dimensional moment |
| $\overline{m}_u$ | Non-dimensional ultimate moment |
| $M$ | Mass matrix, or; |
| | Moment in the beam to upright connections |
| $M_{1Y}$ | First yield point on the moment-rotation backbone |
| $M_b$ | Base plate moment |

| | |
|---|---|
| $M_{BU}$ | Ultimate moment of the beam end connector |
| $M_{CU}$ | Ultimate moment of the beam |
| $M_i$ | The effective or modal mass for mode i |
| $m_j$ | Lumped mass at degree of freedom j |
| $M_{max}$ | Maximum allowable moment of the base plate |
| $M_p$ | Plastic moment of the base plate |
| $M_{p,b}$ | Plastic moment of the beam |
| $M_{ult}$ | Base plate moment, including second order effects |
| $M_u$ | Ultimate moment |
| $M_{max-ups}$ | Maximum moment in first storey uprights |
| $M_y$ | Yield moment |
| $N^*$ | Design value of the vertical action on the frame |
| $N$ | Number of beams at every levels |
| $N_b$ | Number of base plate connections |
| $N_{brace}$ | Number of bracing members in tension |
| $N_{brc}$ | Number of bracing members in the upright frame |
| $N_c$ | Number of beam to upright connection |
| $N_{cr}$ | Elastic critical load |
| $P$ | Pallet load distributed at every beam |
| $p_{cr}$ | Maximum allowable load at every beam level |
| $P_E$ | External work in the down aisle direction |
| $R$ | Seismic Reduction Factor |
| $S_{j,ini}$ | The initial stiffness of the connection |
| $S_p$ | Factor for redundancy of structure |
| $S_{ti}$ | Transverse shear stiffness of an upright frame |
| $T$ | Fundamental period of structure |
| $t_b$ | Brace member thickness |
| $t_c$ | Connector's thickness |
| $t_u$ | Upright member thickness |
| $U$ | Total displacement response of a MDOF structure, or; |
| | Internal work in the down aisle frame |
| $U_E$ | External energy in the base plate assembly |
| $U_I$ | Internal energy in the base plate assembly |

| | |
|---|---|
| $u_m$ | Ultimate deformation of the system in the push over curve |
| $u_o$ | First yield displacement |
| $\ddot{u}_g$ | Ground acceleration |
| $u_y$ | The displacement at which the structure starts to yield (yield displacement) |
| $V_{base\ shar}$ | Seismic base shear in the structure |
| $V_e$ | Elastic base shear at the maximum monitored displacement of the top beam level |
| $V_{max}$ | Inelastic base shear at the maximum monitored displacement of the top beam level |
| $W$ | The total potential energy of the system |
| $Y_n(t)$ | Time varying displacement function |
| $\alpha$ | Parameters for developing hysteresis curves, or;<br>Imperfection (out of plumb), or;<br>Seismic intensity factor, or;<br>The angle between the frame bracing member and the direction perpendicular to the upright |
| $\beta$ | Reduction factor for the cross section area of the bracing members, or;<br>Parameters for developing hysteresis curves |
| $\delta_1$ to $\delta_4$ | Displacements at positions 1 to 4, respectively |
| $\delta_{ci}$ | Maximum allowable rotation of the connection |
| $\delta_{Fail}$ | Final point on the moment-rotation backbone |
| $\delta_L$ | Horizontal deflection at the bottom of the storey |
| $\delta_U$ | Horizontal deflection at the top of the storey |
| $\Delta_e$ | Equivalent elastic response displacement |
| $\Delta_{e,top}$ | Top storey elastic displacement |
| $\Delta_{p,top}$ | Inelastic top level displacement |
| $\Delta_s$ | Stability displacement limit |
| $\zeta$ | Damping ratio |
| $\eta$ | Parameters for developing hysteresis curves |

| | |
|---|---|
| $\theta$ | Drift of the down aisle frame excluding imperfection |
| $\theta_1$. | Maximum first storey inter-storey drift ratio, |
| $\theta_b$ | Relative rotation of base plate connection |
| $\theta_{b,p}$ | The value of $\theta_b$ at failure. |
| $\theta_D$ | The minimum required rotation of the connector to allow a Plastic mechanism to occur |
| $\theta_{top\ storey}$ | Maximum top storey drift ration |
| $\theta_u$ | Ultimate rotation of the beam to upright connections |
| $\theta_{ult}$ | Ultimate rotation of the base plate connectionn |
| $\theta_y$ | Yield rotation |
| $\lambda$ | The factor to convert the multi degree of freedom model to the equivalent single degree of freedom model |
| $\mu$ | Ductility of structure |
| $\sigma$ | Normal stress |
| $\sigma_{ult}$ | Maximum stress at upright-hook interaction |
| $\tau$ | Shear stress |
| $\Phi$ | Dynamic Mode shape matrix, or;<br>Frame imperfection |
| $\bar{\emptyset}$ | Non-dimensional rotation |
| $\emptyset_b$ | The angle between horizontal and diagonal braces |
| $\Phi_b$ | The angle between horizontal and diagonal braces |
| $\Phi_{i,j}$ | Relative deformed shape displacement for mode i at degree of freedom j |
| $\Phi_{max}$ | Largest value of the sway index |
| $\Phi_n$ | Time-independent vector of the system's $n^{th}$ mode shape and |
| $\Phi\mu$, $R_\mu$, q | Ductility of structure |
| $\gamma$ | The angle between brace member and the horizontal direction |
| $\varphi$ | Sway rotation equal to 0.02 Rad, or;<br>Total drift of the down aisle frame including imperfection |
| $\Omega$ | Over Strength Factor |

## Abstract

Industrial racking systems are load bearing structures for the warehouse storage of goods. They are normally fabricated and assembled from cold-formed perforated open thin-walled vertical members and can be 4 meters to 40 meters high. To resist lateral actions such as seismic loads, racking structures rely typically on flexible boltless beam to upright connections along the storage aisles and braced frames in the transverse cross-aisle direction. Compared to their self weight, industrial racks carry very heavy pallet loads as opposed to other conventional structures. High slenderness ratio, heavy pallet loads, connection flexibility and low degree of redundancy make rack structures very different from conventional steel structures. Therefore, in the racking industry special analysis and design codes are adopted which require specific experimental tests to determine the performance of the key structural components. However the current standards do not give sufficient guidance for seismic design. This PhD research investigates both numerically and experimentally the effect of different connections on the performance of industrial racking systems. The research focus is on three critical connections: (a) Beam-upright connection; (b) Floor connection (Base-plate connection); and (c) Bolted brace connection. Courtesy of Dexion Australia, part of the research was based on test results conducted on their racking components. More than 70 beam to upright connection tests including monotonic and cyclic tests, 15 base plate tests under combined axial and bending loads and 4 full cross aisle shear frame tests were studied. FE models were then developed and verified against the test results. Further FE analyses revealed the behaviour of the aforementioned local connections under monotonic and cyclic actions and as a result simple theoretical models were proposed. After deep investigations on the performance of different connections of a typical rack structure, more than 20 full scaled shake table tests were conducted to reveal the dynamic features of a rack structure and one full scaled static cyclic push over test was performed to evaluate the system deterioration under cyclic actions. Both dynamic and static full scaled tests were accurately modeled using the proposed beam to upright connection model. A new performance based seismic analysis approach was proposed at the end of the thesis which showed much more accurate results compared to the seismic analysis approach in the current racking codes and specifications.