STUDY BEHAVIOUR OF SELECTIVE RACKING SYSTEMS IN THE CROSS-AISLE DIRECTION

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ABSTRACT

This paper describes the behaviour of selective steel storage racking systems in the cross-aisle direction. Steel storage racks are regular kind of equipment; these systems are developed for enhancing the storage of load units in diverse weights and sizes. In most cases in this study, the boundary conditions assumed fixed on their fundamental state, to prevent from any possible moment – rotation and uplift effects on uprights. Finite element method (FEM) modeling was used to analyze and evaluate the natural frequency of diagonally k-braced frame at cross-aisle direction. This report takes advantage of capabilities of two well-known structural analysis software for FEM modeling: Abaqus and Strand7. The objective is to predict and determine the eigenvalues and natural frequencies of selective steel storage racks in the cross-aisle direction. Taking the fact into account that the reaction of the structure under seismic loads is vitally important at this critical direction, this paper will provide a better view for designing these type of structures in the future. The novelty of this paper is to classify conditions where we could avoid creating any possible resonance in the structure.

KEYWORDS

Selective steel storage racks, natural frequency, cross-aisle direction, structural optimization, finite element analysis.

INTRODUCTION

Steel storage racking systems are facilities used in approximately 40% of the manufacture, distribution and consumption cycle of all products, these systems are developed for enhancing the storing load units in diverse weights and sizes. Selective rack systems are very cost-effective and offer suitable accessibility of all stored goods for all periods of time during their life-cycle. It is an ideal system where full selectivity and speed of operation are the key objectives, with the added advantages of ease of customization and adjustability. These features made selective racks the most common type of storage racks in use today. However, there is a problem with these systems, their natural frequency is relatively high when seismic loading applies and limited guidelines for their design is available. Racks are challenging to design because they are built as lightly as possible,but are very heavily loaded, and they can fail and collapse for a range of reasons. This paper aims to determine the forces leading to these collapses and providing a better view for the design of these structures accordingly. A standard selective storage racking system is illustrated in Figure 1.

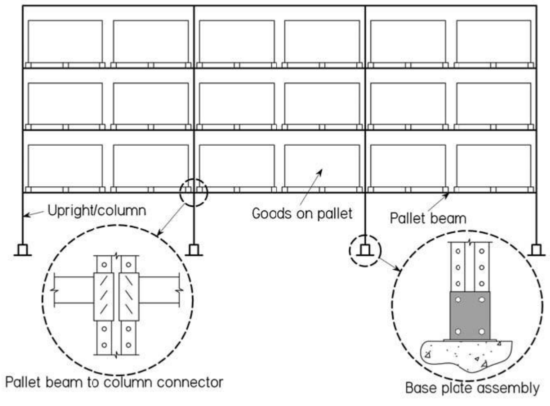

Figure1 Standard selective storage rack (Gilbert and Rasmussen 2012)

Uprights at racking systems are typically made of thin-walled cold-formed steel sections that contain ranges of holes along the longitudinal axis of the member. The perforations can be assumed as a kind of undesirable features which has to be supposed in addition to the other type of imperfections. Therefore, a perforated section is further ‘‘imperfect’’ over an unperforated one (Crisan et al. 2012). Uprights and load beams are the main parts of selective pallet racks. The upright capacity needs to be higher than the overall capacities of the load beams in a “bay” or section of rack, and is a factor of the type of steel, and the depth and height of the upright. The standard height of an upright frame starts from 3 meters to 12 meters, and covers the working compression load from 7.5 to 12.5 tons per frame. Similarly, there is a wide range of standard working load for beams from 1 to 4 tons per level (Australian Standard AS 4048 2012).

Selective racks are free standing assemblies that carry gravity loads, placement and impact forces and possibly seismic forces. In the cross-aisle direction (lateral direction), the uprights are linked together by bracing members. It is highly possible for the uprights to be influenced by lateral forces and consequently deflect and fail sideways. In the down-aisle direction (longitudinal direction), the frame is normally designed as a moment resisting frame. Since steel storage racks are typically unbraced in the down-aisle direction, the stability relies heavily on the beam to column joints and the connection at the point of base plate (Freitas et al. 2010). It was found that the capacity of energy dissipation and ductility for storage racks is much greater in the down-aisle moment-resisting direction in comparison to cross-aisle braced frame direction (FEMA 460 2005).

In steel storage racking systems, lateral stiffness in the down-aisle direction is ordinarily provided by beam-to-column joints and base-plate connections. Baseplate joints have great influence on the overall rack response and, therefore, more tests should be conducted on the behaviour of the column base restraint to achieve more data. In most cases, joints should be modeled as hinges (Baldassino and Bernuzzi 2000). Trouncer carried out several experimental investigations on uprights, and according to the nature of the buckling tests and defined pinned boundary conditions for the major principal axis, it was discovered that overall buckling was the dominant failure mode, regardless of the length of the specimen tested. However for the shorter sections, both local and distortional buckling typically occurred well before overall buckling, meaning that there was an interaction between the buckling modes which lead to a reduction in the upright’s axial stiffness (Trouncer 2013).

The objective of this paper is to attain a better view on the behaviour of steel storage rack structure in cross-aisle direction, with the main focus on evaluating the natural frequency and the overall response of the system, which could be the most critical direction for any failure in these types of structures. This will provide better solutions for designing these types of structures in the future.

METHODOLOGY

Finite Element Modelling of Selective Steel Storage Rack

To attain “Natural Frequency” and different modes of the structure in free vibration condition, two finite element method (FEM) modeling software were used for analyzing and evaluating behaviour of the rack frame in cross-aisle direction, respectively Abaqus and Strand 7. Boundary conditions assumed fixed for preventing from any moment – rotation and uplift effects on uprights in both of Abaqus and Strand 7 software. To study the natural frequency of the structure through FEM, the step for analysis defined as “Linear Perturbation – Frequency” in Abaqus. However, the solver assumed “Static Solver” for doing analysis in Strand 7.

Model Geometry and Element Types

The units for modeling considered SI units, newton (N) and meter (M) throughout all modeling. The length of upright at all models assumed generally 5.8 m for RF9015 standard section. Howerver, The length of bracing considered 1176 mm for diagonal bracing and 992 mm for horizontal bracing. The side view of rack model illustrates at Figure 2.

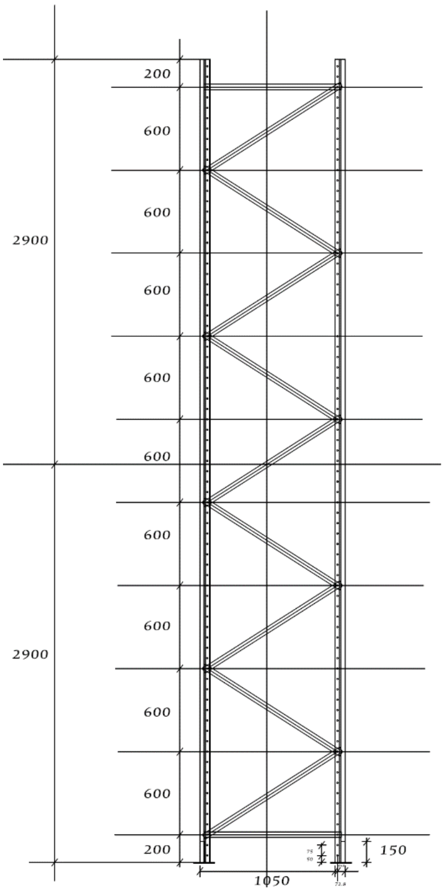

Figure 2 Side view of model

In Abaqus modeling, uprights and bracing defined as “Shell Element”. Similarly, in Strand 7 modeling, upright defined as “Shell Element”, while bracing is considered as “Beam Element”. In a whole rack system analysis in Strand 7, the distance between two frames assumed 2.4 m, while 1.5 m assumed as a constant distance between two diaphragms.

Materials and Sections Properties

Table 1 presents section properties for upright used in modeling.

Table 1 Upright with lip stiffener section properties

Name	Depth (mm)	Width (mm)	Lip (mm)	Thickness (mm)
RF9015	88.5	72.8	15.5	1.5
Area (mm^2)	$I_{\text{Principal-axis}}$ ($10^6 \times mm^4$)	$I_{\text{Minor-axis}}$ ($10^6 \times mm^4$)	J (mm^4)	I_w ($10^6 \times mm^6$)
413	0.0435	0.0284	310	59.2

Table 2 determines section properties for bracing cee section used in modeling.

Table 2 Cee section properties

Name	Depth (mm)	Width (mm)	Lip (mm)	Thickness (mm)
Cee Section	40	23	7	1.5

Table 3 indicates material properties for different elements in modeling.

Table 3 material properties

Element Type	E (MPa)	Poisson’s Ratio	ρ (kg/m^3)
Upright	225E3	0.25	7850
Bracing	200E3	0.25	7850

Since the main focus of this study was evaluating the overall response of steel storage rack structure systems, in case of modeling and analysis in the Strand 7 software, uprights modeled without any perforation details which seems to have minor effect on natural frequency analysis results of the structure.

RESULTS AND DISCUSSIONS

The finite element method is a powerful numerical technique that uses variations and interpolation methods for modeling and solving boundary value problems associated with distributed-parameter vibration problems. This method is also extremely useful for complicated structures with unusual geometric shapes such as trusses and frames (Inman 2013).

Free vibration occurs when a mechanical system is set off with an initial input and then allowed to vibrate freely. Natural frequency is the frequency at which a system naturally vibrates once it has been set into motion, a key aspect of structural dynamic analysis concerns the behaviour of a structure at "resonance". Resonance occurs when the forced vibration of an object matches the natural frequency of the self-weight of the structure. In general, the total value of any response is the combination of the contributions of all the vibration modes. Mass and stiffness are two important factors for determining the natural frequency. Moreover, length of structural elements and speed of vibration wave has a great impact on the natural frequency of a structure (Randall 1987). The first modes should always consider as the most critical mode for designing rack structures.

Results of Abaqus for In-plane Restraint Single Upright Analysis

The figure 3 illustrates natural frequency analysis results for in-plane restraint single perforated upright for different modes in Abaqus.

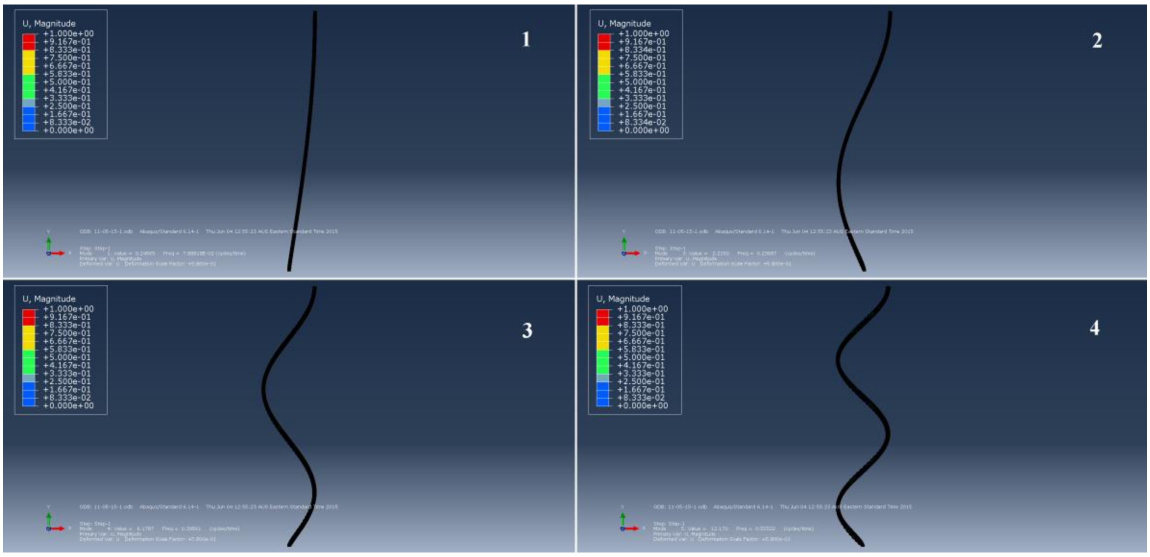

Figure 3 Natural frequency analysis results for In-plane single upright analysis

Table 4 clarifies a summary of natural frequency analysis results for in-plane restraint single upright for different modes in Abaqus.

Table 4 Natural frequency results for in-plane restraint single upright analysis

Mode	Eigenvalue	Frequency (Hz)	Period (Sec)
Mode 1	0.24565	0.0788818	12.6771955
Mode 2	2.2150	0.23687	4.221724997
Mode 3	6.1787	0.39561	2.527741968
Mode 4	12.170	0.55522	1.801087857

Results of Strand 7 for In-plane Restraint Frame Analysis

The figure 4 displays natural frequency analysis results for in-plane restraint frame for different modes in Strand 7.

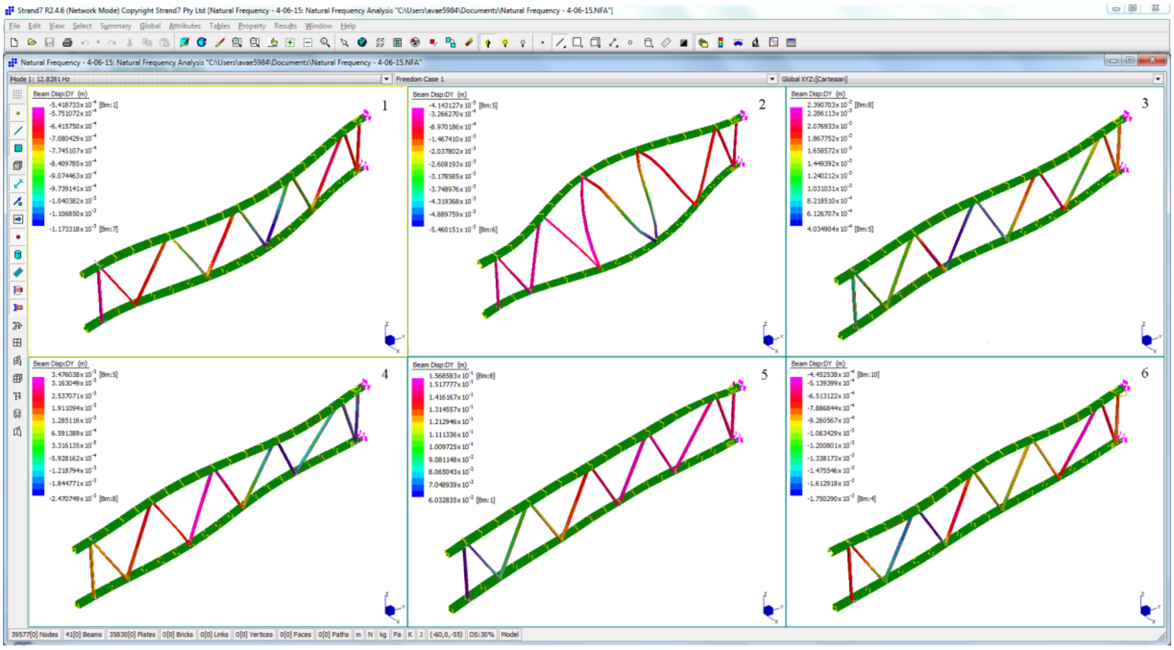

Figure 4 Natural frequency analysis results for In-plane restraint frame analysis

Table 5 shows a summary of natural frequency analysis results for in-plane restraint frame for different modes in Strand 7.

Table 5 Natural frequency results for in-plane restraint frame analysis

Mode	Eigenvalue	Frequency (Hz)	Period (Sec)
Mode 1	9.27181664E+03	15. 3251	0.065252429
Mode 2	1.13356867E+04	16.9451	0.05901411
Mode 3	3.88595512E+04	31.3739	0.031873627
Mode 4	4.40200290E+04	33.3922	0.029947113
Mode 5	5.77304415E+04	38.2404	0.026150354
Mode 6	8.77523117E+04	47.1465	0.021210482

Results of Strand 7 for Whole Rack System Analysis

Figure 5 illustrates natural frequency analysis results for a whole rack system for different modes in Strand 7.

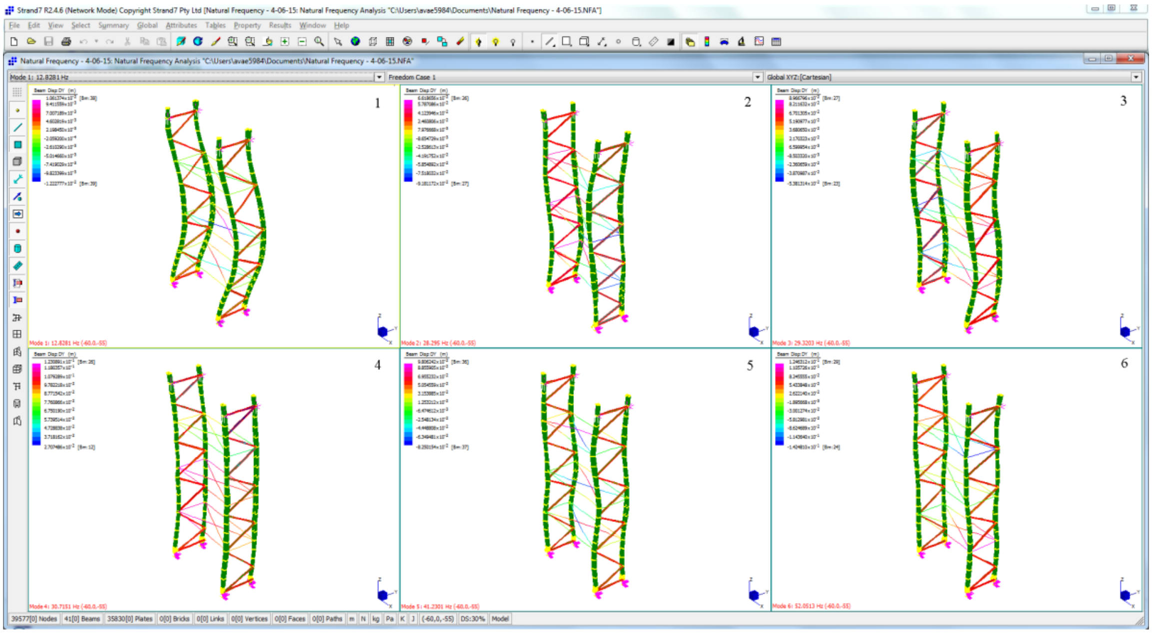

Figure 5 Natural frequency analysis results for whole rack system analysis

Table 6 indicates the summary of natural frequency analysis results for the whole rack system for different modes in Strand 7.

Table 6 Natural frequency results for whole rack system analysis

Mode	Eigenvalue	Frequency (Hz)	Period (Sec)
Mode 1	6.49662255E+03	12.8281476	0.077953578
Mode 2	3.16067937E+04	28.2950426	0.03534188
Mode 3	3.39389164E+04	29.3203478	0.034106007
Mode 4	3.72446294E+04	30.7151019	0.032557274
Mode 5	6.71103075E+04	41.2301340	0.024254105
Mode 6	1.06960442E+05	52.0513174	0.01921181

The results for natural frequency analysis are entirely conservative and could just be considered as a starting point for getting more familiar with the behaviour of the steel storage rack systems. These results clarify some possible vibration modes and approximate deformation of the structure under self-weight free vibration condition.

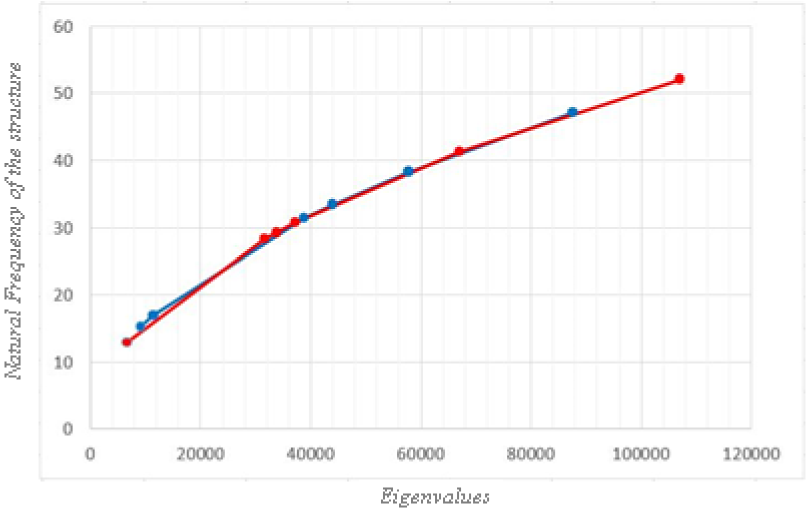

Figure 6 Eigenvalue and natural frequency diagram

Figure 6 illustrates that there is a logarithmic relation between eigenvalues and natural frequencies of the rack structures. The blue line illustrates In-plane restraint frame analysis and red line indicates values for whole rack system analysis , which coincide with each other, this resemblance confirms the validity and accuracy of the results. And generally shows that both of value increases with each other in a logarithmic trend which indicates upper limits for designing the rack structure.

The friction force between pallets and rail beams makes pallets act as links to connect adjacent rack uprights, so the pallets are beneficial factors to increase the lateral stiffness of storage racks. Compared with unloaded racks, the natural frequencies of loaded racks are smaller (Cheng and Wu 2013).

The vibration response can be reduced by achieving certain spacing between two adjacent natural frequencies. For instance, when the excitation frequency lies between two natural frequencies, the suitable design is to maximize the distance between the excitation frequency and the nearest higher and the nearest lower frequency. The natural frequencies of structures can be modified by different methods such as changing the boundary conditions and adding internal supports, adding auxiliary structures, such as masses and springs and changing the structural geometry, thickness and modulus of elasticity (Bendsoe and Olhof 1985).

Lower frequencies means the structure takes more time to return to its initial (pre excited) situation which means that the structure is in a more vulnerable situation to seismic load and have more capacity of critical fracture, deformation and displacement. One of the main limitation is the material capacity to deform plastically without any fractures or cracks.

It is vitally significant to find resilient design solutions for shifting a natural frequency of the structure, to avoid a coincidence between an excitation and a modal response. Reaching higher range of frequency at last modes for a structure means that the structure has a greater natural potential for damping lower frequencies and applied forces which put the structure in a safer situation in terms of structural stability, strength and steadiness. The Period and frequency of a structure had a reverse relationship with each other, it means that structure with lower natural frequency has longer one cycle vibration period. We cannot change a lot on the quantity of mass of the structure, but we can optimize the damping and internal stiffness of a structure for a better sustainable and desirable design.

All Structures undergo some shape changes under load. In stable structure the deformations induced by the load are typically small, and internal forces are generated in the structure by the action of the load that tend to restore the structure to its original shape after the load has been removed (Schodek and Bechthold 2014).

Lack of restraining causes relatively low frequency which means higher possibility of torsion, bending and huge dispalement , which could ultimately resulted in catastrophic deformation and buckling in the structure. The natural frequency analysis for in-plane restraint single perforated upright could be consider as an example for this case, that behave like a cantilver beam.

Bracing an upright changes its buckling mode and consequently its effective length. The more an upright is braced, the shorter its effective length becomes and the greater the load that is required to cause buckling. Bracing is usually more effective when placed symmetrically (Schodek and Bechthold 2014).

The bracing configuration plays a great role in the natural frequency of rack structures, plan bracings at the top and spine bracings at the back of the rack can change the load transfer through the rack framework, strengthen the initial lateral stiffness of racks, but only back spine bracings can affect the natural frequency and damping ratio of racks (Gilbert and Rasmussen 2009). Furthermore, using x-bracing or double bracing ideas could be so hepful for imporving seismic behaviour of rack structures in the cross-aisle direction.Experimental studies revealed that the seismic response of rack systems in the down-aisle direction is greatly influenced by nonlinear moment-rotation response of the beam to upright connections. However, the seismic response in the cross-aisle direction relies on the specifications of the bracing members used in the truss arrangement (FEMA 460 2005).

As a general rule in structural analysis, higher stiffness at structure results in higher and more critical natural frequencies. So it is beneficial to decrease the natural frequency of rack structures through having a relatively ductile base plates, allowing a bit uplift at the base point of uprights and improving the overall response of the frame in the cross-aisle direction under high seismic loads.

The Natural frequency of vibration increases by structural stiffness and steadiness. The greater the displacements, the greater the stresses that are developed in the framing members and connections of the structure. Reinforcing the structure and uncoupling the vibration sources are the two main options to correct those problems which greatly reduce the vibration amplitude by stiffening the structure (Schodek and Bechthold 2014).

It is highly essential to damp out the mechanical motions through flexible competent structural design and using damping equipment. For instance, perforation in steel storage rack structure's upright plays a great role for flexibility of uprights for deforming and absorb and damp seismic energy beside the main role that have on the adjustability of setting a desirable configuration for racks. However, they are currently considered as a structural imperfection. Taking the fact into account that, this kind of design shouldn't pass the boundaries of strength and affects the ideal performance of the structure. This topic should be considered as a real concern and boundary for future design optimization of steel storage racks.

One of most common procedures for decreasing effects of seismic loads is base isolation, which diminishes the horizontal acceleration in structures. Filiatrault et al. accomplished tests on anchored and base-isolated steel pallet storage racks. The instrument operated in the tests provided base isolation in the cross-aisle direction, while the down-aisle direction had similar restraint conditions as the conventional ones. The structures with cross-aisle base isolation showed better seismic performance by reducing the cross-aisle absolute accelerations and inter-story drifts (Filiatrault et al. 2006). More experimental and numerical studies should conduct for revealing capability and weakness of these structures for damping forced vibrations. The natural frequency and damping ratio are not only important in free vibration, but also characterize how a system will behave under forced vibration. If no damping exists, there is nothing to dissipate the energy and therefore theoretically the motion will continue to grow on into infinity (Schodek and Bechthold 2014).

This study evaluated the natural frequency of the structure in the cross-aisle direction, for the first time through FEM modeling that could be the main strength of this research. Which it was not possible through analytical and experimental procedures.

CONCLUSIONS

This paper could suggest a simplified method to predict the natural frequency of the rack system. By considering author's knowledge, currently there are quite limited number of published papers that predicted natural frequency of rack structures. The novelty of this paper is to classify conditions where we could avoid creating any possible resonance in the structure. Accuracy was the first priority of the author in these series of modeling. At every step of modeling, it was hardly tried that come up with models that be accurate as much as possible. Furthermore, geometry and properties defined as closest as possible to the real case situation.

This kind of calculation of natural frequency for rack systems could be useful to find out critical vibration modes of the structure and provide a better overall view for the design of this type of structure. This would prevent conditions that could lead to the resonance phenomenon of the structure due to external forces or seismic loading.

This paper also could be helpful to recognize the location of the week points at the structure and improve the design guidelines in that area to optimize behavior of structure under seismic loads and providing better structural solutions. This method of modeling could be extended to the full selective rack systems on larger scales and also could be useful for the studies on behaviour of drive-in rack systems.

Ductility and flexibility as a general idea could be a great solution for improving the overall response of these structures. In turn, this will decrease the quantity of the natural frequency during free vibration of these structures.

From a writer's point of view, some complementary modelling and numerical analysis should be conducted for validating and improving the accuracy of results for design guidelines. It is also highly recommended that the results compare and get updated with some possible corresponding experimental and analytical analyses to attain better views on the topic. Some of natural frequency modes (combination of flexural and torsional condition) are still vague and needs to further researches undertaken in this area.

It is also recommended that other damping possibilities should studied at rack systems for near resonance vibrations to provide some solutions for decreasing natural frequencies. This effect naturally occurs through deflection of members in the absence of any damping equipment such as base isolation and viscous damper ideas at general steel structures. Furthermore, Hand calculating critical value for buckling either as single columns or as a group of columns needs to be taken into account for further studies.

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