A Simplified Computational Model for Beam-Type Steel Storage Racks Based on Modal and Seismic Analyses

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Abstract. The objective of this study is to develop a simplified computational model for beam-type steel storage racks. In this study, simplified models for double-row and single-row beam type steel racks, based on tributary bays of the spline bracing, are established and their modal analysis and dynamic characteristics under seismic action are compared with the corresponding full rack models. The results show that the fundamental periods and modes, and the lateral displacements under seismic load, are very close between simplified models based on one unit rack with the spline bracing and the full rack model. Hence, this indicates that the seismic analysis of the rack could utilize one unit rack with spline bracing instead of the full rack model, which can greatly improve the computational efficiency.

Introduction

The steel storage rack commonly manufactured with cold-formed steel profiles has a wide application in storage industry[1]. Beam-type steel rack is one of the most commonly used one[2]. Rack, as a frame-type structural system, utilizes a large number of members. For large storage racks, the number of these members can be more than tens or hundreds of thousands, which renders the computational analysis very expensive[3]. To reduce the computational expensive and efficiency and thus reduce the design difficulty, simplified models are needed.

In this paper, a unit rack, consisting of tributary bays based on the spline bracing, is selected as a unit rack model based on the uniform load distribution among the spline bracings. The results of the modal analysis and lateral displacements under seismic of the unit rack model are compared with those of the full rack model to determine the feasibility of the unit rack model as a representative of the full rack model for seismic analysis.

The finite element model

The beam-type racks can be single-row or double row. A double row rack adopts a back-to-back layout of two single-row racks. The studied racks are modeled using SAP2000 with beam elements. The rack has 11 stories with a story height of 1.95m, which results in a 22.8m total height. The upright is N120 as shown in Figure 1 and beam uses K120x50 as shown in Figure 2. All members use Q235 steel. The base plate is assumed to be pinned. The beam-to-column connection adopts the semi-rigid behavior based on the low-cycle reversed loading experiment of the Speedlock beam-to-
column connectors from the author’s research group\textsuperscript{[4]}. Thus, the stiffness of the connection is taken as 116\text{kN} \cdot \text{m/rad}\textsuperscript{[4]}. There is restraint in out of plane at the top of the rack. A uniform gravity load of 2.78 \text{kN/m} is put on the beam. The seismic precautionary intensity is 7 and the design basic acceleration of ground motion is 0.1g. Seismic site is category III and group 1 for seismic group. The design characteristic period of ground motion is 0.45s. The seismic response analysis method adopts the base shear method from rack design code\textsuperscript{[5]}. 

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Upright section (N120) \hspace{1cm} Welding beams section (K100x50)}
\end{figure}

\textbf{A simplified model of a double-row storage rack}

The double-row storage rack consists of 32 bays with 4 spline bracings. Based on the tributary distribution of the loads among the bracings, 8 bays including one spline bracing was chosen as a unit rack. Their modal analyses of the unit rack and full rack models were conducted and the first three modes and their fundamental periods are provided in Figure 3 and also summarized in Table 1.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure3.png}
\caption{The first three modes and their fundamental periods of two models(double-row storage rack)}
\end{figure}
Table 1 The first three modes of two models (double-row storage rack)

<table>
<thead>
<tr>
<th>Model</th>
<th>Vibration mode and period</th>
<th>First mode</th>
<th>Second mode</th>
<th>Third mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full rack model</td>
<td>Vibration mode</td>
<td>Translation along down-aisle direction</td>
<td>Translation along down-aisle direction</td>
<td>Translation along cross-aisle direction</td>
</tr>
<tr>
<td></td>
<td>Period(s)</td>
<td>1.20</td>
<td>0.92</td>
<td>0.72</td>
</tr>
<tr>
<td>Unit rack model</td>
<td>Vibration mode</td>
<td>Translation along down-aisle direction</td>
<td>Translation along down-aisle direction</td>
<td>Translation along cross-aisle direction</td>
</tr>
<tr>
<td></td>
<td>Period(s)</td>
<td>1.22</td>
<td>0.95</td>
<td>0.70</td>
</tr>
</tbody>
</table>

As can be seen from Figure 3 and Table 1, the first three modes has negligible difference between the full rack and unit rack models, with a maximum difference of 3.26% in mode 2.

Meanwhile, the lateral displacement of the two models under the seismic loading in cross-aisle and down-aisle directions are shown in Figure 4. The maximum lateral displacement at the top of the rack is provided in Table 2.

Table 2 The maximum lateral displacement at the top of the rack (double-row storage rack)

<table>
<thead>
<tr>
<th>Model</th>
<th>Cross-aisle direction /mm</th>
<th>Down-aisle direction /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full rack model</td>
<td>9.060</td>
<td>25.268</td>
</tr>
<tr>
<td>Unit rack model</td>
<td>8.361</td>
<td>26.137</td>
</tr>
</tbody>
</table>

Comparing the predicted maximum lateral displacement in two models, the differences are small in both seismic cases. Specifically, the difference is 7.72% between the two models in cross-aisle direction while it is even much smaller in down-aisle direction with a difference of 3.44%.

A simplified model of a single-row storage rack

The single-row storage rack has a similar dimension of the double-row storage rack with 32 bays and 4 spline bracings. The unit rack model was selected in a similar fashion as the double-row rack. Figure 5 and Table 3 provided and summarized the modal analysis results.
Full rack model (T=1.14s)  Unit rack model (T=1.16s)
(a) First mode

Full rack model (T=0.73s)  Unit rack model (T=0.71s)  Full rack model (T=0.72s)  Unit rack model (T=0.67s)
(b) Second mode  (c) Third mode

Figure 5 The first three modes and their fundamental periods of two models (single-row storage rack)

Table 3 The first three modes of two models (single-row storage rack)

<table>
<thead>
<tr>
<th>Model</th>
<th>Vibration mode and period</th>
<th>First mode</th>
<th>Second mode</th>
<th>Third mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full rack model</td>
<td>Translation along down-aisle direction</td>
<td>1.14</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>Unit rack model</td>
<td>Translation along down-aisle direction</td>
<td>1.16</td>
<td>0.71</td>
<td>0.67</td>
</tr>
</tbody>
</table>

As can be seen from Figure 5 and Table 3, the first three modes have negligible difference between the full rack and unit rack models, with a maximum difference of 6.94% in mode 3.

The lateral displacement of the two models under the seismic loading in cross-aisle and down-aisle directions are shown in Figure 6. The maximum lateral displacement at the top of the rack is provided in Table 4.
Similar to the double-row rack models, the differences of the predicted maximum lateral displacement are small in both seismic cases. Specifically, the differences are all smaller than 5%.

Conclusions

This paper explored the feasibility of a simplified unit rack model, consisting of tributary bays based on the spline bracing, in predicting the behaviors of the full rack. Based on the modal analyses of the unit rack model and the full rack model for double-row and single-row racks, the fundamental modes and periods of the two models agree well. In addition, the maximum lateral displacement of the two models under seismic loading under both the cross-aisle and down-aisle directions show negligible difference. Thus, the unit rack model proposed herein can be potentially used a simplified yet efficient model for computational analysis of the full rack structures.

References


