Stability of Automatic Storage and Retrieval Rack Systems at Elevated Temperatures

Zheng Peng and Artemis Agelaridou-Twohig

Center for Property Risk Solutions
FM Global, Research Division

1151 Boston Providence Turnpike
Norwood, MA 02062

Abstract*: Automatic Storage and Retrieval Systems (ASRS) are computer-controlled systems for handling products in storage facilities with minimal manual labor. The combination of densely stored goods, height of structures, large number of interconnected racks, and tight geometrical tolerances raises concerns of structural damage to the system when exposed to elevated temperatures. Structural damage of this type could potentially lead to long down-times while the affected unit is being repaired or loss of building integrity when the rack is part of a building's structural support. The behavior of typical single- and multiple-row ASRS racks was investigated. An effective method was established, which allowed to avoid full three-dimensional analysis, and to study the behavior of large and complex ASRS units at elevated temperatures. The evaluation indicates that a simple structural analysis, based on removal of selected column supports, could be considered equivalent to a coupled thermo-mechanical analysis method considering elevated temperatures.*

Keywords*: ASRS, Storage Racks, Elevated Temperature, Structural Damage.*

1. Introduction

Automated Storage and Retrieval Systems (ASRS) vary from relatively simple, manually controlled order-picking machines operating in small storage structures to large, computer-controlled storage/retrieval systems that are integrated into a manufacturing and distribution process.[1] The latest generation of ASRS systems offers an effective tool for those in warehousing and distribution to achieve greater throughput, reduce errors and damage and gain better control of inventory. These systems are reaching greater heights allowing companies to expand vertically rather than horizontally, thus reducing or eliminating the need of acquiring more real estate.[2]

The stability of rack structures has been studied in the past. For examples, van Hauwaert[3] discussed the safety of racking storage systems and the factors that may cause collapse and extensive damage. Lewis[4] investigated a simple design approach to the problem of stability of rack systems. In his approach, the loads were assumed uniformly distributed on the rack frames and the bending distortion of the frames was neglected. A relationship between the maximum loads of pallet rack frameworks with respect to the frame end connecting characteristics and the initial out-of-plumb of the structure was derived. Ng et al.[5] studied the collapse behavior of rack structures due to structural damage using the finite element method. The model had five levels and five bays with a width and height of 1.5 m each. Individual bottom legs were taken out one at a time and the buckling and maximum loads were determined. Ng et al.[6] further investigated progressive collapse behaviors of the rack structure assuming a single leg is removed by impact. The most critical position was found to be the lowest members of the rack structure. A progressive collapse was found to occur when one frame leg was removed under an increased service loading condition for the rack structure studied. Dynamic analysis was used to analyze post-collapse behaviors of the rack structure studied. Affolter et al.[7] investigated the collapse of a storage rack that resulted in one fatality. By using the finite element analysis method, buckling loads were estimated considering various geometric and load imperfections. It was concluded that the failure of the rack structure could be attributed to a static overload of the frames. However, all of these studies were focused on conventional storage racks, rather than the light-gauge ASRS racks with rows interconnected to form a system. There are some reports of analytical and experimental investigations of elevated-temperature-induced structural responses. For example, Popov et al.[8] performed numerical analysis on steel frame behavior subjected to fire temperatures using an elastic plastic material physical model with allowance for variation in material thermo-mechanical properties. Ali et al.[9] estimated the separation distance required between single-story steel frames and firewalls, which accounted for the temperature-dependent steel properties to predict the steel temperature at which the plastic hinges form. However, no studies have been found that are related to the ASRS systems exposed to elevated temperatures.

Critical questions we seek to answer in this study, assuming a small section of the rack is exposed to high temperatures, include: (1) will the affected area collapse?, and (2) if the affected area collapses, will the rack areas that are not directly affected by elevated temperatures sequentially collapse, causing extensive damage of the entire ASRS system?

2. TYPICAL ASRS COMPONENTS

General information on ASRS systems was collected and analyzed and is briefly summarized here. Most ASRS systems are based on three basic sub-systems: (1) two rows of metal racks facing each other with an aisle in between, (2) a “crane” or “robot” moving along each aisle and transporting goods, and (3) a raised metal rail down the center of the aisle and sometimes additional rail running at the top of the aisle used to guide the cranes. These three sub-systems form a functional ASRS assembly. Multiple assemblies are usually tied together back-to-back at the top, forming a full system. The typical ASRS system used in this study consists of rack frames, horizontal ties, diagonal bracing, across-aisle tie, and top rail as shown in Figure 2.1 and Figure 2.2. Material properties are listed in Table 2.1.

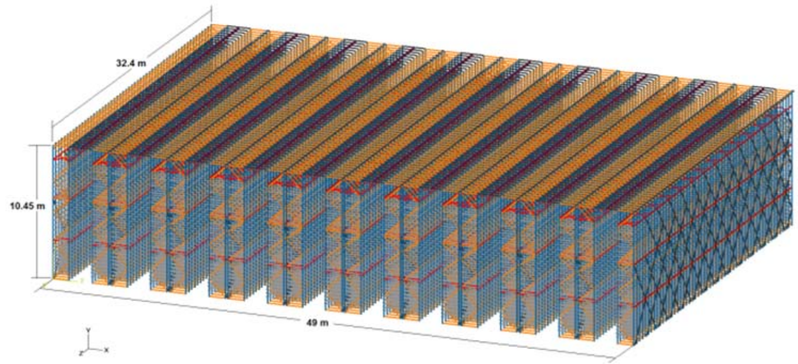


Figure 2.1 Isometric view for a typical ASRS rack system.

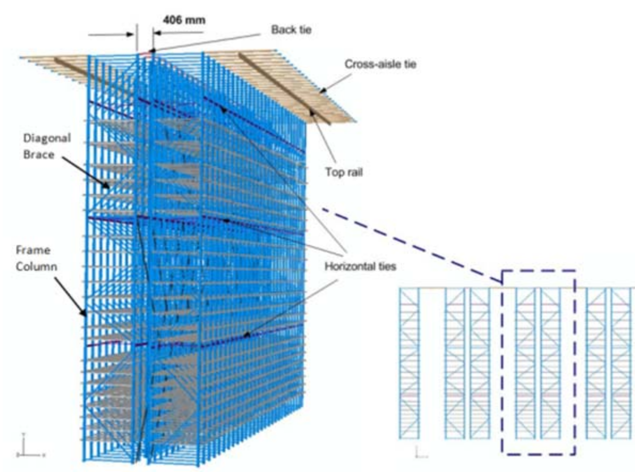


Figure 2.2 Typical rack components.

Table 2.1 Material properties.

	Material Name	Modulus of Elasticity (GPa)	Yield Stress (GPa)	Poisson's Ratio
Frame Column	A653M	203	0.345	0.3
Horizontal Tie	EN 10147 S 250 GD		0.250	
Diagonal Brace	A36 G40		0.248	
Top Rail	EN 10147 S 250 GD		0.250	
Cross-aisle Tie	EN 10147 S 250 GD		0.250	

3. INVESTIGATION OF BASIC STRUCTURAL BEHAVIOR

We started with a one-row rack model (Figure 3.1), as a basic block of an ASRS system. This model includes 19 bays (20 pairs of frame columns laced with diagonal braces) formed with three basic types of components: frame column, in-rack diagonal brace, and horizontal tie. Upright frames are installed in parallel in the "along-aisle" direction with their plane parallel to the "across-aisle" direction. Horizontal ties connect frames together in the along-aisle direction.

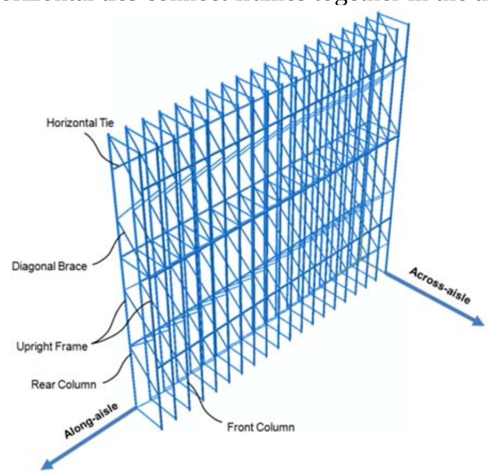


Figure 3.1 A 19-bay rack model.

In this model, three-dimensional open-section beam elements are used for all the structural members. For simplicity, connections are assumed rigid, and therefore there is no relative motion or rotation at the connections. Commodity loads are applied on the columns, at heights corresponding to the various tiers of storage. The loads on the columns of the two end frames are half of those on the columns of the middle frames because they are only supporting loads from one rack bay each. The front frame columns, those facing an aisle, support 55% of the bay loads and rear frame columns support 45% of the bay loads. There are 22 tiers of storage in the vertical direction with each storage location rated for a maximum load of 670 N (151 lbs). In the following analysis, normalized load is defined as a multiple of the maximum rated service load. Both geometry and material nonlinearities are considered.

3.1 Buckling Loads – Standard Temperature

The buckling loads were determined using a two-step static analysis in Abaqus/Standard V6.10:[10]

- Step I (static): application of rack gravity, and
- Step II (static): application of commodity loads.

Rack buckling is assumed to follow, or simultaneously happen, with a sudden increase in the vertical displacements at the top of the rack when the critical load is reached.

Figure 3.2 illustrates the vertical displacements at the rack top, as the commodity loads increase with analysis time (Step II time units are proportional to 5 times the normalized loads, i.e. analysis time of 1.0 corresponds to Step time II of 0.0 and a normalized load of 0.0, analysis time 1.2 corresponds to Step II time of 0.2 and a normalized load of 1.0, etc.). Initially, the vertical displacements appear to increase proportionally with the loads. The analysis aborted at a time of 1.78 (0.78 time units of Step II) due to numerical instability. The Step II time of 0.78 corresponds to a normalized load of 3.9. Due to the problems with convergence using a simple static analysis, the vertical displacements do not show an abrupt increase at the end and it is unclear if the load of 3.9 represents the buckling load of the rack structure.

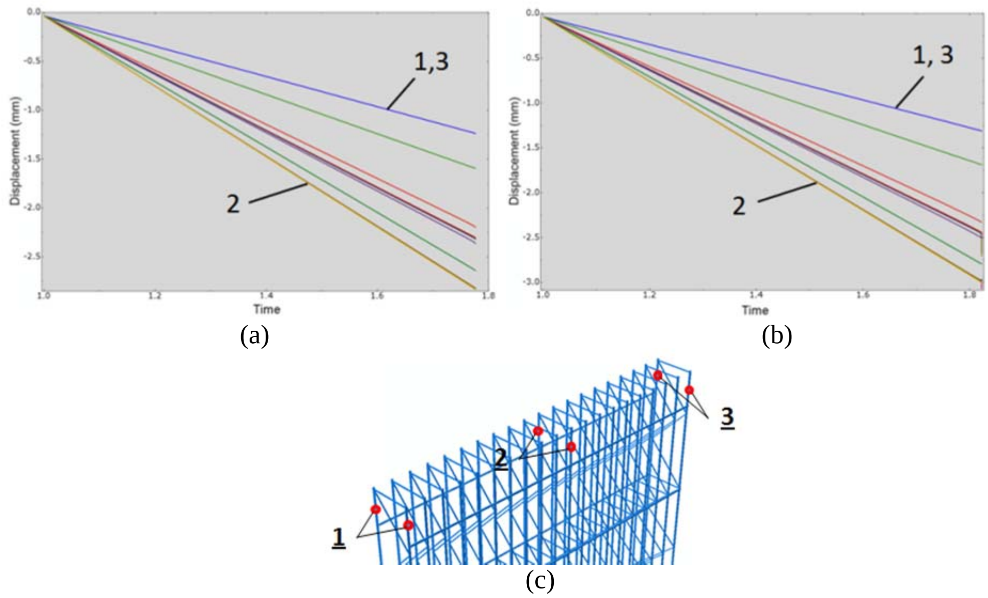


Figure 3.2 Vertical displacements at the rack top: (a) without automatic stabilization, (b) with automatic stabilization, and (c) locations of output.

When the automatic stabilization function was turned on, with the dissipated energy fraction of 0.0002 and the maximum ratio of stabilization to strain energy of 0.001, which are the default values specified in Abaqus,[10] the convergence issues did not occur until a Step II time of 0.82 units, which corresponds to a normalized load of 4.1, a 5% increase over the maximum load reached with the previous analysis when automatic stabilization was not considered. In addition, some indication of abrupt increase in vertical displacements did develop. As means of verification, we used the same structural model to perform a linear eigenvalue analysis and a RIKS analysis. These two methods resulted in a buckling load of 4.07 and 4.10, respectively, which are in line with the results of the static analysis. Still, however, only limited post-buckling responses have been revealed.

In an attempt to further extend the runs to better reveal the post-buckling response, the Implicit Dynamic solver was used to analyze the same rack structure. Two steps were defined:

- Step I (static): application of gravity and a preloading of 3.5 normalized load, and
- Step II (implicit dynamic): application of a dynamic loading of 0.3.

Duration of Step I was set to a nominal time of 1.0 while Step II was set to run for a real time duration of 10 seconds. The 0.3 dynamic loading was applied as a ramp in the first 4 seconds and maintained constant for the rest of Step II. The total applied load was 3.8, which is slightly smaller than the normalized load at buckling of 3.9 derived from the static analysis. The selection of 4 seconds to apply the linearly increased dynamic loading of 0.3 was arbitrary. It was chosen as to have reasonable CPU usage and to minimize the dynamic effect when the load was applied. Other durations were tried, e.g., 8 and 12 seconds, with no noticeable impact on the results. The dynamically applied portion of the 0.3 normalized load was also arbitrary. When the full load of 3.8 is applied, the magnitude of the dynamically applied part does not significantly influence the results, as long as it is relatively small compared with the total load.

Additional studies were performed to increase the dynamic load to 0.4 for a total load of 3.9 and further to 0.5 for a total load of 4.0. The vertical displacements at the rack top are illustrated in Figures 3.3 for the three cases. When the total load is lower than the static buckling load of 3.9, the vertical displacements at the frame top increase linearly as the load increases and remain constant as the load becomes constant (Figure 3.3a). When the total load is substantially close to or marginally higher than 3.9, oscillation of the vertical displacements at the rack top develops and is maintained even after the load becomes constant. The oscillation in displacements is a typical indication that the rack structure is on the verge of buckling (Figure 3.3b). When the total load is higher than 3.9, a structural collapse develops as evidenced by a sudden increase of the vertical displacements at the rack top (Figure 3.3c), even before the full load of 4.0 is applied. The structural collapse is also demonstrated by the deformed shape of the rack shown in Figure 3.4, where red areas at the lower portion of the frame columns indicate exceedance of the yield stress and extensive plastic deformation.

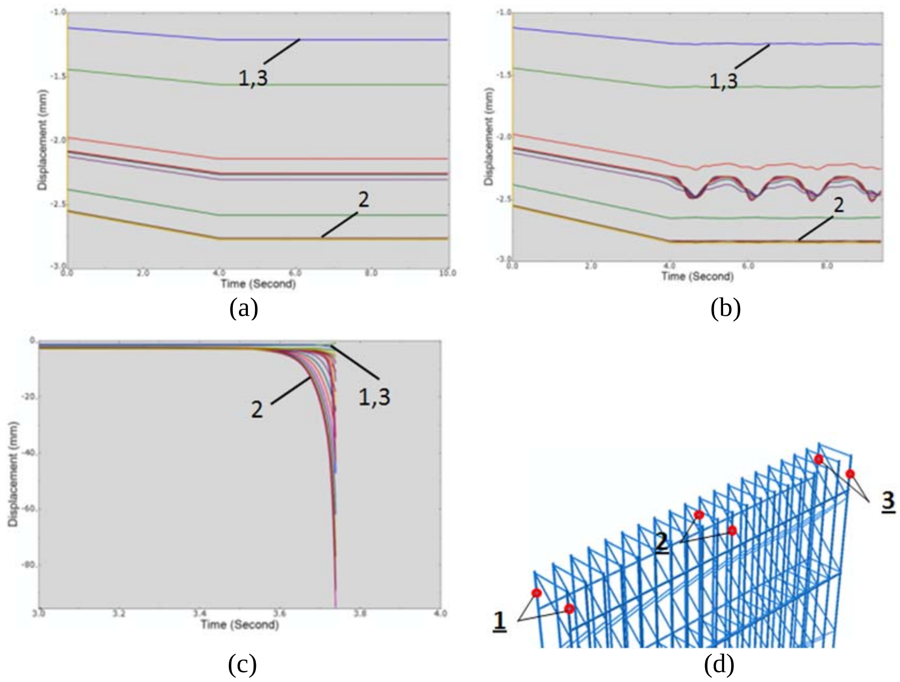


Figure 3.3 Vertical displacements at the rack top: (a) total load of 3.8, (b) total load of 3.9, (c) total load of 4.0, and (d) location of output.

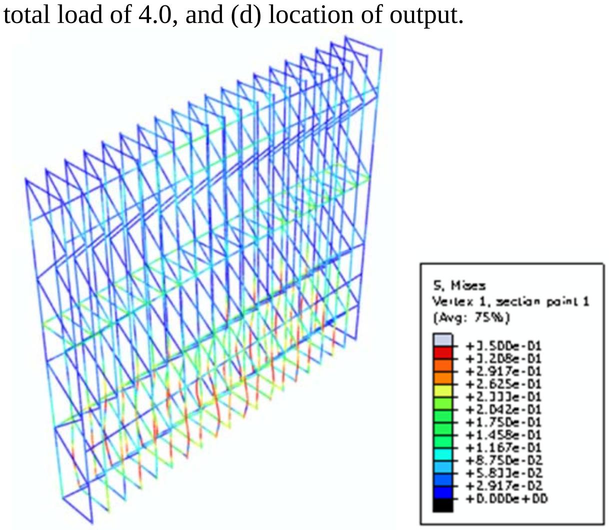


Figure 3.4 Deformed rack structure (yield stress for the frames is 0.35 GPa).

3.2 Elevated Temperature Response

When a metal experiences temperature rise, its strength decreases. In this study, the temperature dependence of Young's modulus and yield strength for steel were calculated based on the mathematical equations given in the SFPE Handbook,[11] as shown in Figure 3.5. Both Young's modulus and yield stress decrease as the temperature rises. At 1000ºC, the steel material loses its strength completely. The influence of thermal expansion was neglected.

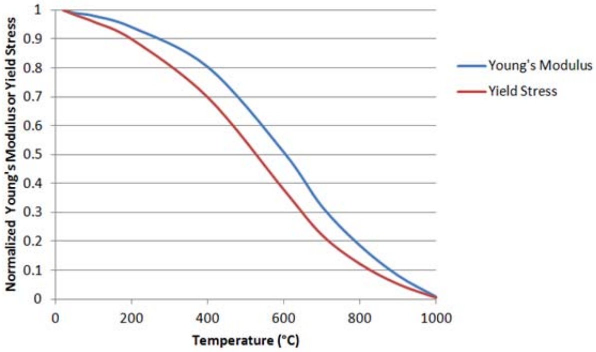


Figure 3.5 Reduction of Young's Modulus and Yield Stress with temperature.[11]

We assumed that a certain number of frames were exposed to elevated temperature uniformly from bottom to top. Starting from one end of the rack structure, the number of frames weakened by temperature was varied from 2 through 20. Figure 3.6 illustrates the critical buckling loads for various temperature levels vs. the number of frame columns heated. With an increase of the temperature-affected area, the critical load decreases quickly and then stabilizes at a certain level, after which the extent of the rack portion exposed to high temperature does not affect the load capacity reduction.

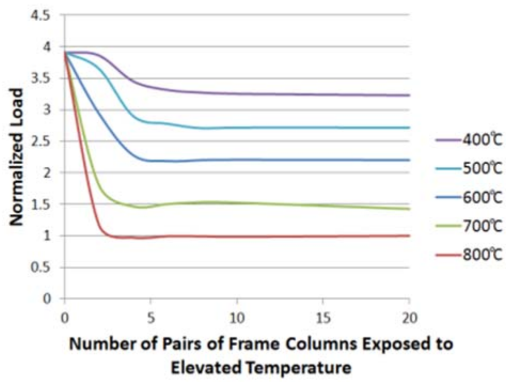


Figure 3.6 Critical buckling load vs. the extent of rack exposed to elevated temperature when the heated area is at the end of a single-row rack.

The heated area controls the numerical stability of the analysis, and consequently the collapse of the structure. When the heated area is small, the unheated part of the rack helps stabilize the structure and the decrease of the buckling load compared to a rack at room temperature is limited. However, with the increase of the heated area, the stabilizing effect diminishes, causing the critical load to be determined by the temperature of the heated area. Figure 3.6 shows the results when the heated area is at the end of the single-row rack. When the heated area is in the middle of the rack, the buckling loads for various temperatures remain the same, but a longer heated section is required for the loads to reach constant levels due to the fact that the heated section is supported from both sides. In other words, when the heated area is large enough, the buckling loads are actually controlled by the temperature level, rather than the location of heating. Therefore, the static analysis can predict the load that causes buckling of the heated area but does not give an indication whether the rest of the rack can provide enough stability for the system to remain stable or to collapse completely.

The data provided in Figure 3.6 can be used to verify whether damage will occur in the heated area, assuming a given temperature. For example, if we are interested in the scenario of an elevated temperature of 800ºC, by looking at Figure 3.6, we can conclude that the rack is marginally stable at the rated service load.

Although this study conservatively involved heating of the full height of a section of the rack, the critical area that is subject to temperature rise is the lower portion of the columns. This was confirmed by an additional study where only the bottom quarter of the rack was heated, which virtually resulted in the same results as when the entire rack was at elevated temperature. Heating the upper part of a section of the rack is not as severe as heating the bottom.

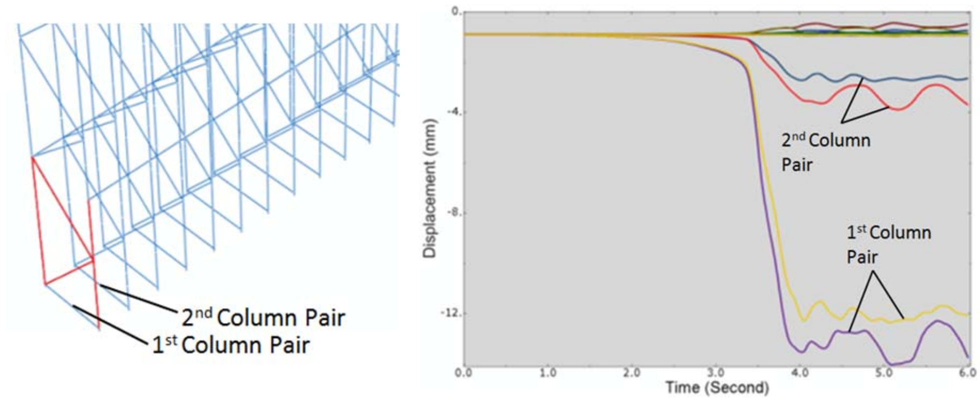
3.3 Progressive Collapse due to Elevated Temperature

Progressive collapse is a sequential, domino-type structural failure. It represents a situation in which local failure of one or more primary structural components leads to the collapse of adjoining members that, in turn, leads to additional collapse. In this case, the failure of a large part of a structure is initiated by damage or failure of a relatively small part. When a portion of a rack heats up, local structural members may lose their strength in a short period of time. This abrupt change in load-supporting capacity of the rack structure may cause local collapse and the local collapse may, in turn, lead to a progressive collapse of the entire structure.

We assumed that the entire structure initially was at a uniform room temperature. The rated design load plus a 30% safety margin[a] was used as the load that the rack structure should support. In ANSI MH16.1: 2012, a 1.4 load factor is used to design for critical limit state of gravity load and a 1.2 load factor is used for critical limit state of dead load.[12] This load was added as equivalent lumped masses on the columns, at heights corresponding to the various tiers of storage. All 6 degrees of freedom of the bottom of the frame columns were fixed. The lower portion of one pair of frame columns from one end of the rack structure (Figure 3.7a) was heated up to 980ºC in 4

[a] Since no safety margin for elevated temperature has been specified in any standards or codes, the 30% safety margin was chosen for demonstration of the analysis method.

seconds. The selection of 980ºC was arbitrary. It was chosen to make sure that the temperature-affected area would virtually lose all of its strength.



(a) (b)

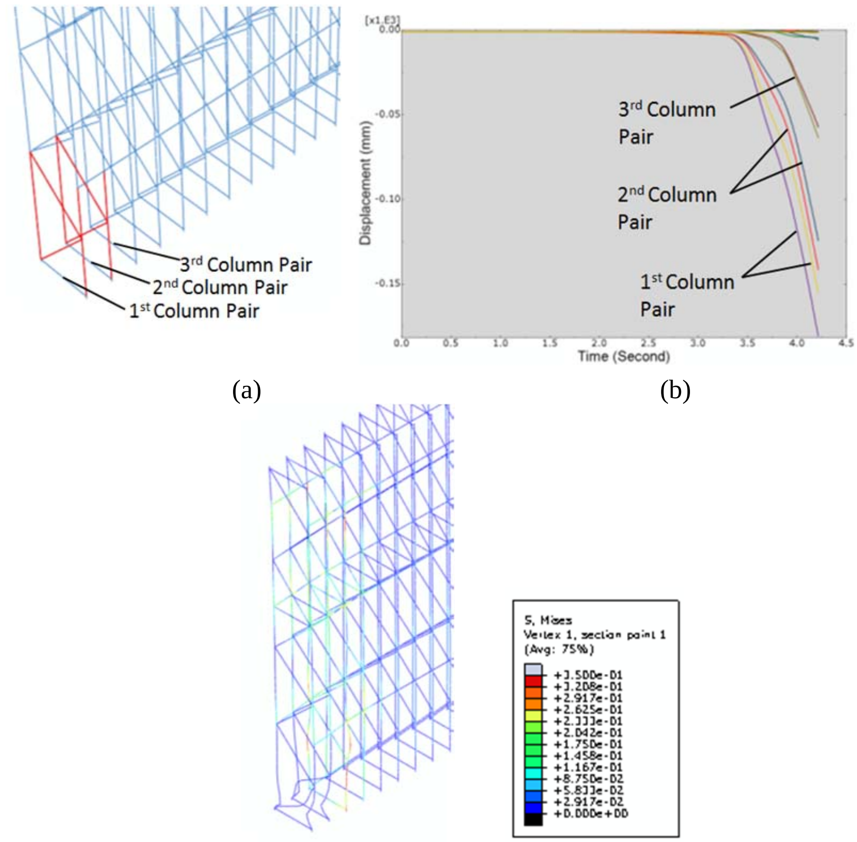
Figure 3.7 Temperature-affected area (a) and the vertical displacements at the rack top (b).

Figure 3.7b shows the vertical displacements at the top of the rack with the increase in temperature of the affected area. The single-row rack remains stable even as the temperature-affected area exhibits severe deformation. No collapse has occurred.

Figure 3.8a shows the scenario when the lower portion of two consecutive frame columns was heated up to 980ºC in 4 seconds and Figure 3.8b shows the vertical displacements at the top of the rack. Figure 3.8c illustrates the deformed structure at about 4.2 seconds indicating that the heated area collapses and the immediate adjacent frames experience severe plastic deformation. It is thus reasonable to assume that these adjacent frames have buckled and collapsed as well. A further extension of this assumption is that, with the collapse of the third pair of frame columns, a fourth one will collapse, etc., causing a domino-type chain response that is a clear indication of progressive collapse.

When the heated area occurs in the middle of the rack row, more frames are required to be heated in order for the structure to progressively collapse. This result is due to the stabilizing effect of the unaffected areas from both sides of the heated section.

When the lower portion of more than two pairs of columns from one end of the single-row rack is heated up to a certain temperature, the heated area will collapse and subsequently cause progressive collapse of the structure in the along-aisle direction. When the heating takes place in the middle of the rack, four or more pairs of columns are required to be affected by temperature in order for the structure to progressively collapse.



(a) (b)

(c)

Figure 3.8 Heated area (a), the vertical displacements at the rack top (b), and (c) the deformed rack structure (yield stress for the frame columns is 0.35 GPa).

3.4 Ground Support Loss

A simpler way to analyze progressive collapse induced by elevated temperatures is to assume that the complete loss of the supporting capability of the lower portion of frame columns due to heating is equivalent to the ground support loss of the corresponding frame legs. When pairs of frame column supports were removed, we derived similar behavior for the rack structure as presented in Section 3.3, i.e., heating one pair of columns was not critical, while heating two or more pairs caused progressive collapse. The tables below illustrate the loading capacity for different ground support loss scenarios.

Table 3.1 documents the results when one pair of frame supports is removed from the rack end. The missing pair of frame supports is designated as 1, 2, 3, etc. sequentially from one end of the single-row rack structure. The worst scenario is when the first pair of frame columns has missing supports, having a residual loading capacity of about 2.41. When the missing supports are located in the middle, farther away from the rack end, the loading capacity approaches 3.0. The rack structure will, therefore, not exhibit collapse under the rated design load plus a 30% safety margin.

Table 3.1 Loading capacities when one pair of frame columns has missing supports.

Missing Supports	**1**	**2**	**3**	**4**	**5**
Loading Capacity	2.41	2.86	3.05	3.04	3.03

Table 3.2 shows the results when two pairs of frame column supports are removed. The worst damage to the rack structure occurs when the four missing supports are located on the first two pairs of frame columns. The minimum residual loading capacity is 1.23. The damage becomes gradually less as the four missing supports are farther away from the rack end. When the missing supports are located in the middle, the minimum residual capacity stabilizes at about 2.04. The rack structure will be unstable when the rated design load plus a 30% safety margin is applied.

Table 3.2 Loading capacities when two pairs of frame columns have missing supports.

Missing Supports	**1 and 2**	**2 and 3**	**3 and 4**	**4 and 5**	**5 and 6**
Loading capacity	1.23	1.82	2.03	2.04	2.04

Table 3.3 illustrates the results when three pairs of frame supports are removed. Only two scenarios were analyzed for simplicity: (1) when the three missing support pairs are all located at one end of the rack, and (2) when the missing support pairs are located in the middle of the rack. Results show that when the three missing support pairs are located at one rack end, the residual loading capacity is about 0.80, which is lower than the rated design load. The rack structure, therefore, will experience collapse.

Table 3.3 Loading capacities when three pairs of column supports are missing.

Missing Supports	**1, 2, and 3**	**7, 8, and 9**
Loading Capacity	0.81	1.45

3.5 Impact of a Collapsing Row of Racks

It is important to investigate the stability of the minimum functional ASRS assembly with two single-row racks connected together on either side of an aisle, and to understand if heating and collapse of one row will or will not cause the other row to collapse. For simplicity, we focused on the scenario of uniform collapse of one of the rows due to heating of the lower portion of all the columns to 980ºC, as schematically shown in Figure 3.9. As in the previous study, the temperature rise was applied in 4 seconds.

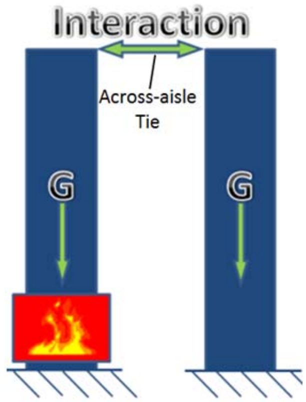


Figure 3.9 Schematic set-up of a collapse scenario of two interacting single-row racks. G refers to gravity loads.

The rack system was loaded with the rated commodity load increased by 30% to introduce a safety margin. The lower portion of the left row of racks (about 2 m or 6.5 ft high from the bottom) was heated to 980ºC in 4 seconds starting from a static equilibrium state. Figure 3.10 shows the evolution of axial section force, von Mises stress, and equivalent plastic strain (PEEQ, as defined in Abaqus[10]) in the across-aisle ties, Figure 2.2, at the location close to the frame columns on the right side. The three curves are plotted together in Figure 3.10 against the same time axis to better show the evolution of events.

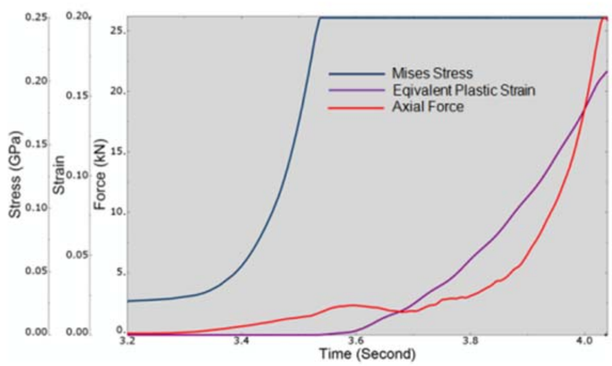


Figure 3.10 Evolution of von Mises stress, equivalent plastic strain, and axial force in the across-aisle ties.

As temperature rises, which is linearly evolving with time, the Mises stress slowly goes up until about 3.4 seconds, when the temperature is about 830ºC. A sudden rise in the Mises stress starts at about 3.4 seconds and reaches a plateau at about 3.5 seconds, when the material of the across-aisle ties close to the frames goes into yielding (0.25 GPa). The Mises Stress remains in yield until the simulation terminates. Accordingly, the equivalent plastic strain exhibits an accelerated increase when the material is yielding and almost linearly increases to over 15% when the simulation terminates. Corresponding to the material yielding, the axial force within the across-aisle ties reaches a local plateau at about 3.6 seconds, indicating a redistribution of loading. The axial force starts to pick-up at about 3.8 second and increases to as high as 25 kN (5,600 lbs) when the simulation terminates slightly after 4 seconds.

Figure 3.11 illustrates a deformed structure at a late stage. The bottom of the temperature-affected racks has totally collapsed. The across-aisle ties have been stretched into straight lines hanging between the frames of the two rows of racks. The upper portion of the row of racks that is on the right hand side has gone into plastic deformation and obvious rotation/bending of the top of the frame has occurred. A substantially large area of the racks on the right hand side experiences plastic deformation following frame buckling.

The across-aisle ties may fail due to excessive plastic deformation at the connections to the frames. A simpler way of introducing a failure mechanism is to monitor the equivalent plastic strain and set a cut-off value. This methodology is schematically demonstrated in Figure 3.12. As the green line indicates, if we assume the failure of the across-aisle ties is signaled by the equivalent plastic strain reaching 10%, for example, then correspondingly we can find out that at this time the axial force is about 9 kN (2000 lbs), as indicated by the lower right corner of the green line on the red axial force curve. We can find other loading histories until this moment, such as perpendicular force, bending moments, etc. These loading conditions can then be applied to the racks on the right hand side to replace the falling row of racks to evaluate whether the racks on the right hand side will collapse.

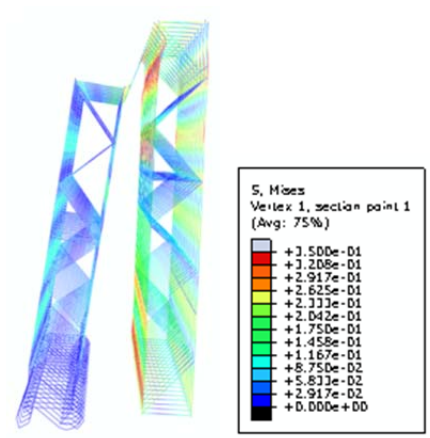


Figure 3.11 Deformed rack structure (yield stress for the frame columns is 0.35 GPa).

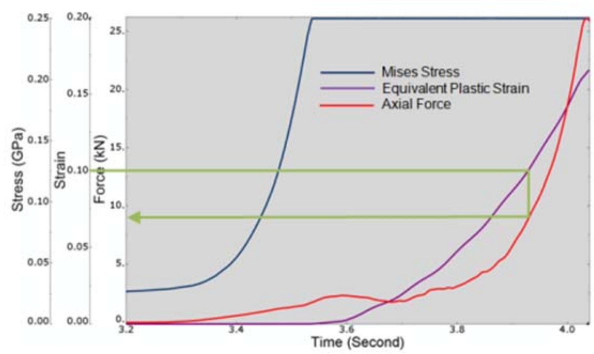


Figure 3.12 Demonstration of a failure mechanism.

3.5.1 An ASRS of Two Rack Assemblies

For the case of two rack assemblies that are connected side by side, if the failure criterion is 20% of the equivalent plastic strain, Figure 3.13 illustrates the lateral displacements at the top of the rack. The top of the rack moves about 50 mm when the across-aisle tie members fail in tension by the collapsed row of racks. However, after the across-aisle tie members fail, the rack top immediately returns to its original neutral position and oscillates about this position thereafter. Observation shows no signs of plastic deformation in the racks. Therefore, it can be concluded that there is no significant damage to the rest of the rack assembly in this scenario.

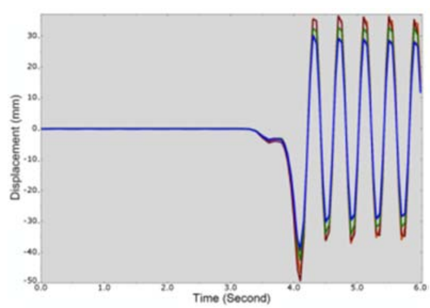


Figure 3.13 Lateral displacements at the rack top for the failure criterion of 20% of the equivalent plastic strain.

However, if the failure criterion is 30% of the equivalent plastic strain, the rack top moves about 150 mm in the lateral direction, as shown in Figure 3.14, when the across-aisle tie members fail. After the across-aisle tie members fail the rack top does not return to its original neutral position, but rather has a residual displacement of about 100 mm and oscillates about this position thereafter. Observation shows widespread plastic deformation in the rack structure. Therefore, disruption to use of racks may be expected. Due to the fact that the ASRS system relies on high precision for positioning boxed commodities on trays, allowed plastic deformation of the racks should be minimal.

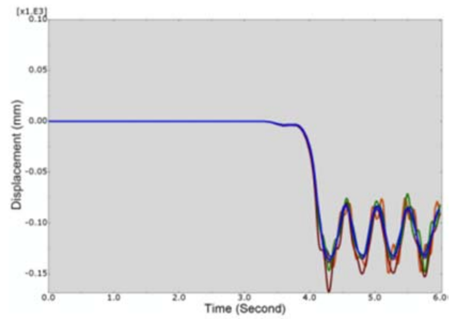


Figure 3.14 Lateral displacements at the rack top for the failure criterion of 30% of the equivalent plastic strain.

3.5.2 An ASRS of Three Rack Assemblies

When three rack assemblies are connected side by side, the forces within the across-aisle tie members connecting the collapsed racks and the rest of the structure are virtually the same as those for the two rack assembly system.

Analysis shows that, when the failure criterion is set at 30% of the equivalent plastic strain, only small areas of the racks on the top develop plastic deformation. Damage is limited and only local repair may be necessary to restore the rack functionality. However, as the threshold of the failure increases to 40% of the equivalent plastic strain, substantially larger areas will develop plastic deformations.

3.5.3 An ASRS of Four and More Rack Assemblies

When four rack assemblies are connected side by side, using the 40% equivalent plastic strain failure criterion, we observe that only the top of the adjacent row of racks develops severe plastic deformation. Sporadic small areas of the rest of the racks develop minor plastic deformation. There is no need to analyze the cases of equivalent plastic strain failure criteria lower than 40% since the damage is localized to the adjacent row of racks.

4. Conclusions

The basic ASRS structural behavior was studied, starting with a single-row rack structure followed by multi-row racks that are interconnected with each other. For a single-row rack structure, loading capacities are inversely related to temperature levels. As more frame columns are affected by local elevated temperatures, progressive collapse might occur in the along-aisle direction. Local elevated temperature high enough to cause failure of the lower rack structure can be deemed equivalent to loss of ground support of the corresponding frame columns. For multiple rack assemblies that are interconnected with each other with across-aisle tie members on the top, the capacity to resist lateral deformation is substantially enhanced. The extent of damage when one or more rows of racks are assumed to collapse is closely related to the failure strength of the across-aisle tie members. Higher failure strength forces more plastic deformation to the immediate adjacent rows of racks and consequently causes more damage. However, total collapse of the entire rack system, if the system has more than four interconnected rack assemblies, is unlikely.

5. Acknowledgement

The authors would like to thank Weston C. Baker, Senior Engineering Technical Specialist, Engineering Standards, FM Global, for his technical advice and for reviewing this paper.

6. References

---

[1] Material Handling Industry of America, AS/RS Industry Group, http://www.mhia.org/industrygroups/as-rs

[2] Morton, R., AS/RS The Heights are Getting Higher, Materials Handling Management, May 13, 2009, http://mhmonline.com/systems-automation/as-rs-heights-higher-6671/

[3] van Hauwaert, P. M., Storage Racks-Gibraltar Solid or Hidden Danger?, Storage Equipment Safety Service Ltd (SESS), http://www.werc.org/publications/publication.aspx?PublicationId=78, accessed on May 20, 2012

[4] Lewis, G. M., Stability of Rack Structures, Thin-walled Structures 12 (1991) 163-174

[5] Ng, A. L. Y., R. Beale, and M. Godley, Dynamic Collapse of Steel Rack Structures, Proceedings of the Eighth International Conference on Computational Structures Technology, Civil-Comp Press, Stirlingshire, Scotland, 2006

[6] Ng, A. L. Y., R. G. Beale, and M. H. R. Godley, Methods of Restraining Progressive Collapse in Rack Structures, Engineering Structures 31 (2009) 1460-1468

[7] Affolter, Ch., G. Piskoty, L. Wullschleger, and B. Weisse, Collapse of a High Storage Rack, Engineering Failure analysis 16 (2009) 1846-1855

[8] Popov, V., E. Jarmolajeva, and A. Jarmolajev, Numerical analysis of steel frame behavior subjected to fire temperature using general method approach, the 10th International Conference on Modern Building Materials, Structures and Techniques, May 19-20, 2010, Vilnius, Lithuania

[9] Ali, H., M., P. E. Senseny, and R. L. Alpert, Clearance between Single-story Steel Frames and Firewalls, Journal of Structural Engineering, January 2005.

[10] Abaqus V6.10, SIMULIA, Rising Sun Mills, 166 Valley Street, Providence, RI 02909-2499, 2010

[11] SFPE Handbook – Fire Protection Engineering, Section 4-9: Analytical Methods for Determining Fire Resistance of Steel Members, 3rd Edition, NFPA, 2002, p.4-212.

[12] ANSI MH16.1: 2012 (a revision of MH16.1: 2008), Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks, approved by American National Standards Institute, Inc., 2012.