Buckling Length Factor of Perforated Column in Steel Pallet Racking

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Abstract *— Stability of multi-story one-bay space pallet racking system studied experimentally and theoretically to obtain the buckling length and the critical load for the upright of the racking system considering the beam-column connection, and frame bracing pattern. Five samples of space pallet racking system are studied to obtain the critical load and buckling lengths with different cases of loading, in addition two samples of short upright of the racking system are investigated under axial compression loads to carry out the upright capacity. The experimental results are re-evaluated using both the American Code of Racking (RMI 2012), and the European code of Racking (EN15512), moreover the investigated system are modeled and analyzed using SCIA Engineer software. The modes of failure of the experimented samples are recorded and evaluated. The experimental program has been conducted on the pallet racks using full-scale models.*

Keywords — *Stability, Pallet Racking, Perforated Column, Buckling Factor, Critical Load***.**

I. INTRODUCTION

Racking systems are load bearing structures for the storage and retrieval of goods in warehouses. The goods to be stored are generally on pallets or in box-containers. Racking is constructed from steel components including upright frames, beams and decking. Special beam to column connections and bracing systems are utilized, in order to achieve a three dimensional 'sway' or 'braced' steel structure with "aisles" to enable order pickers, industrial trucks or stacker cranes to reach the storage positions. Although components are standardized, they are only standard to each manufacturer. These components differ from traditional column and beam structures in the following regard.

1) Continuous perforated uprights.
2) Hook-in connections.
3) Structural components for racking generally consist of cold formed thin gauge members.

The uprights of steel storage racks are generally cold-formed lipped channels. They are braced into upright frames by connecting vertical bracing between the channel lips of opposing channels using bolted connections, Beam is horizontal member made of two C-channel interlocking to form a hollow rectangular section linking adjacent frames and lying in the horizontal direction parallel to the operating aisle, Beam end connector is welded to or otherwise formed as an integral part of the beams, which has hooks or other devices which engage in holes or slots in the upright. Fig. 1 shows complete pallet racking system configuration.

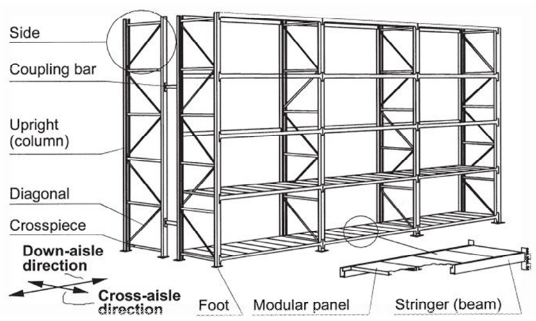


Fig. 1 complete pallet racking system configuration.

The use of cold-formed steel compression members with thin gauge multiple holes sections or with hook-on-connectors are missing solid base for determining ultimate and working capacity under vertical and horizontal loads. Working capacity is typically determined through laboratory tests. A simple change in the system layout requires a new set of tests to evaluate the system and to determine its new capacity. EN 15512 (European Norms) code is available code that deals with the design of static steel pallet racking systems, and it depends primarily on experimental results. RMI (Rack Manufacture Institute) current specification allows the use of the full cross section properties for the perforated columns used in the racking system to predict the overall buckling strength, thus assuming that the presence of such perforation does not have significant influence on the overall buckling strength. The research will focus primarily on regulating the design of rack uprights which are designed partly on an experimental basis. The scope of work will deal with the rack upright in a full-scale system taking the effect of the connecting beams, the results of the space analysis is to be evaluated with the results of the individual member's analysis, and the different design codes

II. LITERATURE REVIEW

Sammy C.W. Lau and Gregory J. Hancock [1], has conducted compression tests on 68 thin-walled channel section columns of different section geometries formed by brake-pressing in fix-ended condition. Design curves to account for the inelastic behavior in the distortional mode of buckling are proposed in the paper and compared with the test results. The test results are also compared with the recently revised Australian Standard, American Specification, and European Recommendations for the design of cold-formed steel structures.

Y. Pu, M.H.R. Godley and R.G. Beale [2], tested 36 stub columns by two different experimental procedures, namely the FEM and AISI procedures, to investigate the difference in the ultimate load between these procedures. It is shown that the failure loads obtained by the two experimental procedures were very close to each other. Both procedures worked well. The AISI procedure is recommended as the standard procedure.

Nabil abdel-Rahman, ashraf fadel, Mohamed. Elsaadawy, and Sherif Mourad [3], Presented an experimental study to investigate the ultimate strength and modes of failure of axially loaded channel rack columns with rear flanges. A total of 16 column specimens fabricated by press-brake forming method were tested up to failure. The test failure loads were compared to the ultimate load predictions of the 2001 AISI North American Specification. The comparison showed that the AISI procedure overestimates the failure load, which suggests that the proportioning of the cross-sectional dimensions of the lipped channel sections with rear flanges has a direct effect on the capacity of the columns.

RMI 2012 (Rack Manufacturing Institute) [4], This code is one of the codes that deals with the Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks, chapter 6 in this code deals with the Rack Column (Upright) under title of "6. Upright Frame Design".

EN 15512 (European Norms) [5], This code is one of the codes that deals with Steel static storage systems - Adjustable pallet racking systems - Principles for structural design, chapter 9 in this code deals with the Structural analysis, the design of column is in session 9.7 under the title "9.7 Compression, tension and bending in members".

SCIA Engineer computer software [6], An structural computer software to model the space racking system under different case of loading, and different profiles for all members, and a good simulation for the beam-column connection, base connection, and frame bracing connection. The software is based on the Eurocode 3 specifications and limitations, it can make linear analysis, non-linear analysis, modal analysis, linear stability (Buckling analysis), and dynamics. The output data that can be extracted from the software are Displacement, internal forces, design Check.

LINKMISR International Company [7], is the biggest company of racking system in Egypt that works under license from the English company LINK51, and it's an associate member in the FEM organization (federation European of manufacturers), also L

INKMISR has the largest market share in Egypt about 80% of the market share. All the profiles used in the experimental study were given by LINKMISR Company.

III. EXPERIMENTAL PROGRAM

Five full-scale steel pallet racking sample are tested in the concrete laboratory at Faculty of Engineering El-Mataria, Helwan University. All of these samples are classified as a full-scale sample with the following characteristics: single bay, two-storey, semi-rigidly jointed, un-braced sway frames. The dimensions of all test samples are identical. These are (2.483 m) wide in the X-direction (Down Aisle), (1.1 m) long in Y-direction (Cross Aisle), (1.232 m) high from the column-base to the first floor, and (1.25 m) high from the first floor to the second floor. Fig. 2 shows the dimensions of the testing samples.

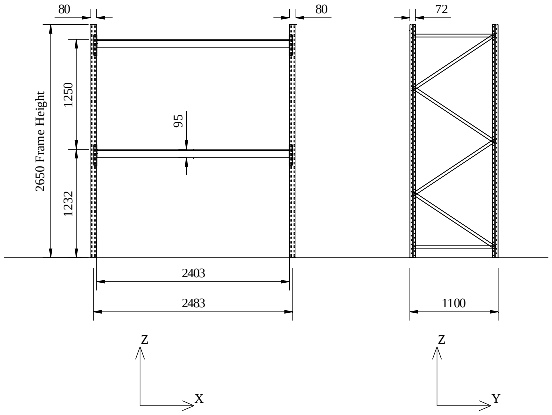


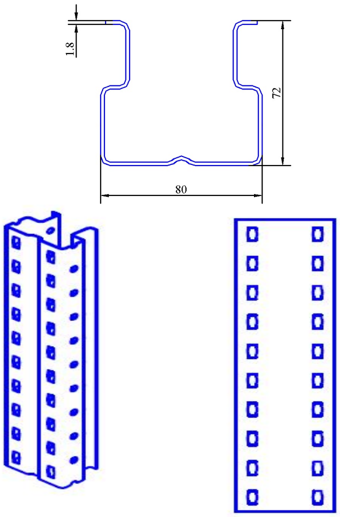
Fig. 2 Dimensions of test sample in mm.

A. *MEMBER PROFILES*

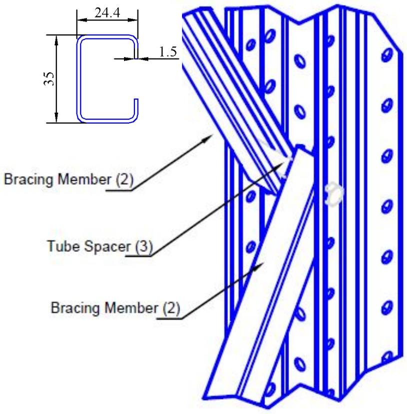
Omega section is used for all column members with 1.8 mm in thickness. Boxed section formed of 2 C-channels interlocked together is used for all horizontal beam members with 1.5 mm thick. C-section is utilized for all frame bracing members with 1.5 mm thick as shown in Fig. 3 and Table (1).

Table (1)
Profile Properties

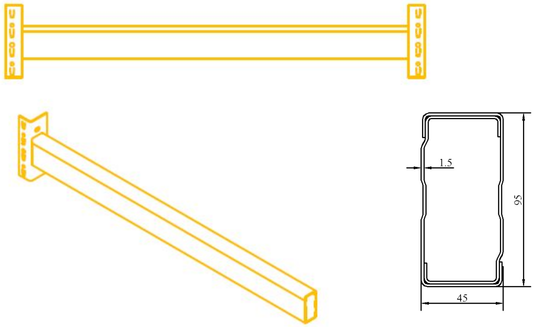
Profile	Th. (mm)	L_T (m)	L_x (m)	L_y (m)	Area (cm^2)	I_x (cm^4)	I_y (cm^4)	r_x (cm)	r_y (cm)
XLUP 80	1.8	2.65	1.25	1.2	3.89	38.33	23	3.15	2.45
XLBB 95YC	1.5	2.4	2.4	2.4	5.82	80.45	18.44	3.7	1.8
XLBR M80	1.5	1.2	1.2	1.2	1.36	2.5	1.1	1.4	.9



Column Upright (**XLUP 80)**



Frame Bracings (**XLBR M80)**



Horizontal Beams (**XLBB 95YC)**

Fig. 3 Sample Profiles.

B. MEMBER MATERIAL

The used material for all members is steel S355j2G3 with yield strength 418 N/mm2, except for Beam-column connector is S420MC with yield strength 426 N/mm2.

C. TEST SAMPLE ARRANGEMENT

Fig. 4 shows the test sample arrangement that consists of four rack uprights, connected in x-dir with four horizontal beams on two levels, and connected in y-dir by frame bracing. the beam-column connection is four hook-on connection, and the frame bracing-column connection is a bolted connection with one bolt m10 grade 8.8, the base connection shown in fig. 4 is a base plate 6 mm thickness., welded to a neck that is connected to the rack upright by 2 bolts m10, the base plate is connected to a rigid concrete floor by 2 m12 floor fixing.

Fig. 4 Test sample arrangement.

Fig. 5 Base Connection.

D. TESTING EQUIPMENT

The Test Samples were tested in a strong floor with loading frame which can sustain (100 ton).

1) LOADING FRAME

The height from the strong floor surface to the top of the loading frame is (3.10 m); all members of the loading frame have rigid cross-sections capable to sustain all cases of loading. Fig. 6

Fig. 6 Loading Frame.

2) HYDRAULIC JACK

(100 ton) hydraulic jack with (100 mm) stroke was mounted at the bottom flange of the loading frame girder in alignment with the centre of the loading system in order to obtain various cases of loading. Fig. 7

Fig. 7 Hydraulic Jack.

3) BOUNDARY CONDITION OF TEST FRAME

The test Bay is pinned at the base level, and the first and second floor levels are semi-rigid hock-on connection in-plane (X-Z dir.) , and hinged in the out-of-plane (Y-Z dir).

4) INSTRUMENTS OF MEASUREMENT

3 dial gauges of (0.1 mm) accuracy connected to LVDT system are used to measure the displacements in the three directions (vertical, in-plane and out-of-plane displacements) for each load increment in mm. These dial gauges are located at the top point of the rack column (Δz), also at mid-span between the horizontal beam (Δx), and the mid-span between two bracing nodes (Δy) (Fig. 8).

Fig. 8 Dial gauges arrangement

5) MEASURE OF IMPERFECTIONS

There are two types of imperfection, local and overall imperfection. The local imperfection had been checked and can be neglected. The overall imperfection had been checked visually and found that it can be neglected.

6) ALIGNMENT

Alignment of the test sample is an important step to be carried out before testing, the alignment of the test sample is achieved using the bracing connection in the Y-dir (Cross Aisle), and beam-column connection in the X-dir (Down Aisle), also the overall alignment of the test bay was measured using a bubble level in all direction.

7) TESTING PROCEDURES

The vertical loads were applied incrementally on the top of one column and other load cases are achieved using the beams loading system see Fig. 9. The test stopped when any column cannot sustain any more load or the displacement appears to be constant with increasing load or the frame collapses. The dial gauge readings are recorded at every load increment. In addition, the critical load was recorded for each model. Note that in this section, Five samples were studied, (S1), (S2), (S3), (S4), and (S5) as shown in Table 2.

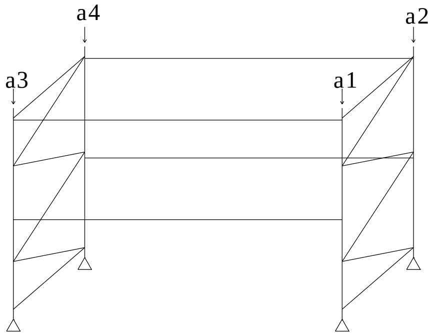


Fig. 9 loading ratios

Table 2
Sample models

Bay	**a_1**	**a_2**	**a_3**	**a_4**
S1	1	0	0	0
S2	0.5	0.5	0	0
S3	0.5	0	0.5	0
S4	0.25	0.25	0.25	0.25
S5	0.3	0.2	0.3	0.2

a = Ratio of the column load over the total load

IV.LOADING PATTERN

The five groups are categorized in according to their loading pattern. S1 is used where the total load is applied directly on the investigated column while S2 is titled for the test where the load is applied on the racking system frame. The load in that case is mostly carried by two columns so a ratio of 0.5 is used to identify that pattern. In setup S3 the load is applied directly on a rigid beam then that load is transferred to the front two columns in the two frames so a factor of 0.5 is used for a single column. In S4 setup the load is carried by the four legs as shown in the next figures so a factor of 0.25 is utilized. The last pattern of loading, S5, is the same as S4 but the loading has some eccentricity with a ratio factor of the studied column of 0.3.

Fig. 10 Loading Pattern S1

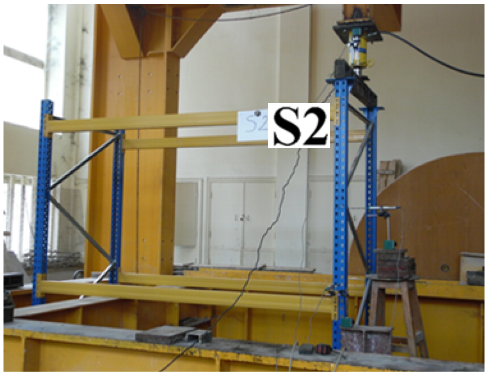


Fig. 11 Loading Pattern S2

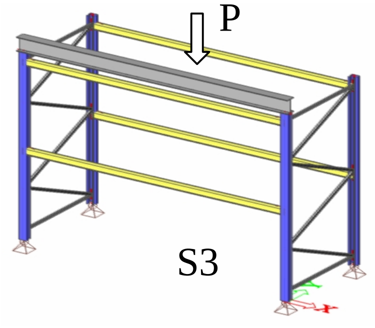


Fig. 12 Loading Pattern S3

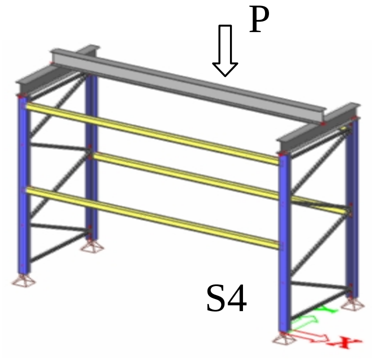


Fig. 13 Loading Pattern S4

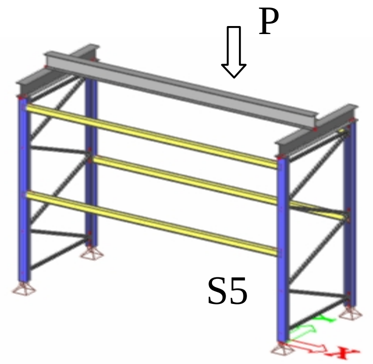


Fig. 14 Loading Pattern S5 with eccentric loading

V. ANALYSIS OF TESTING RESULTS

Fig. 15 shows the relation between the applied axial loads versus the axial displacement of a single column. However the load is applied on more than one column for loading patterns S2 to S5, the load is multiplied by the loading ratio as shown in table 2. The first loading pattern shows the lowest axial stiffness with the maximum load. You may notice that by applying on more than on column the stiffness is degraded however, stiffness enhancement is found for the loading pattern number S4 for the case of uniformly distributed loads on all columns. The maximum load is found for the loading pattern S1 where the load is applied directly on the column. The setup S2 achieved similar maximum load since the column is well braced in the shorter direction of the frame. The ultimate load is substantially reduced for the cases of S3 to S5 where the column suffers buckling in X direction and the horizontal beam does not sufficiently brace the column.

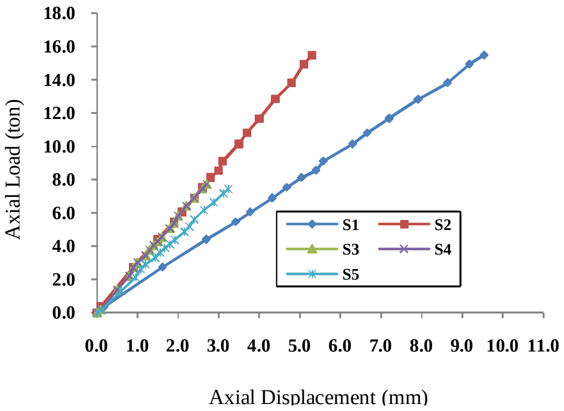


Fig. 15 The relation of the axial load with the axial displacement

Figure 16 shows the lateral displacement in X direction for the tested columns under all of the loading patterns. One can notice that the maximum lateral displacement is found for setup S1 and S2. In addition the loading pattern S1 and S2 have similar curves. You may conclude that the bracing in X direction enhanced the performance of the column in Y direction also. The maximum lateral displacement is found for S5 accompanied with the lowest axial strength.

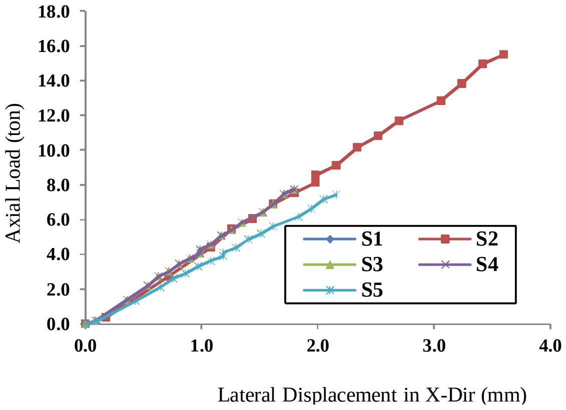


Fig. 16 The relation of the axial load with the lateral displacement (X-Dir)

Figure 17 shows the lateral displacement in Y direction for the tested columns under all of the loading patterns. One can notice that the maximum lateral displacement is found for setup S1. You may notice S2 and S3 have maximum displacement of ~ 1 mm in Y dir. You may conclude that the horizontal beam does not provide enough bracing for the column.

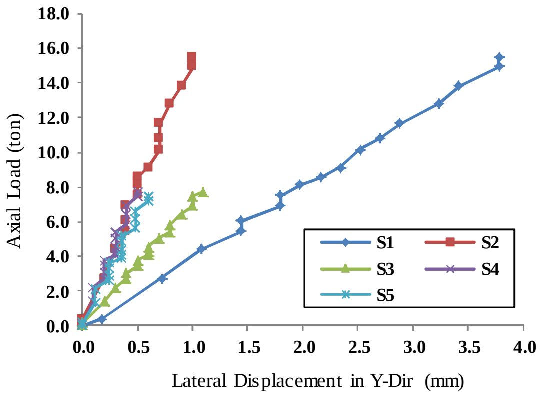


Fig. 17 The relation of the axial load with the lateral disp. (Y-Dir)

Studying the previous curves one can conclude that the critical load is effected by the bracing in X and Y direction with different measures. The resultant of the lateral displacement is calculated for the studied column and graphed with the axial loading. Figure 18 shows the relation between the load and the resultant of the lateral displacements. The loading pattern S1 and S2 have maximum critical loads with larger lateral displacements. That is due to the efficiency of the bracing systems in the Y direction

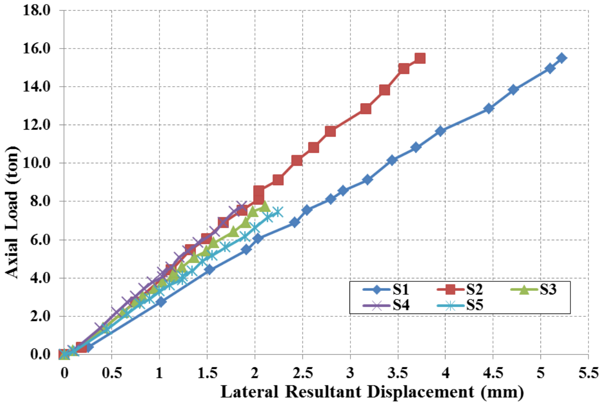


Fig. 18 The relation of the axial load with the resultant of the lateral displacements

Fig. 19 The failure mode of a single column compression loading test

COLUMN FAILURE MODE

A small sample of the columns with length of 50 cm is axially tested under compression loads. The mode of failure is shown in Fig. 19. Also, the mode shapes of the failure for the investigated columns are shown in figures 20, 21 and 22.

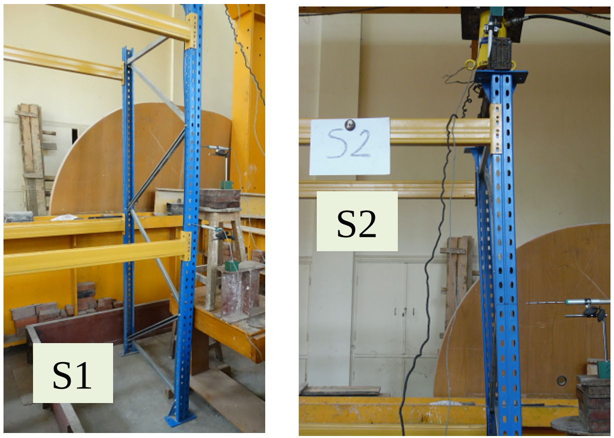


Fig. 20 The failure mode of specimens S1, S2

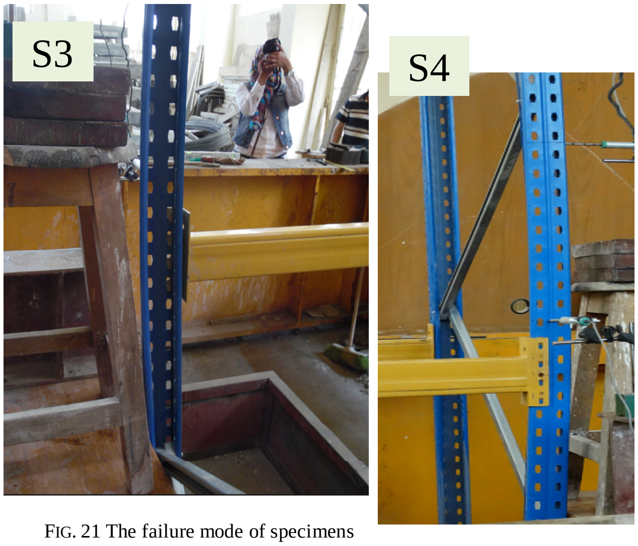


FIG. 21 The failure mode of specimens S3, S4

Fig. 22 The failure mode of specimens S5

BUCKLING LENGTH FACTOR

To calculate the buckling factor of each system the Euler load is calculated where, $P_E = \pi^2 EI/L^2$. Then P_E = 30.5 ton for all column samples. The critical loads P_{cr} are measured for all specimens as the failure load. Then the buckling length factor, $K = (P_E/P_{cr})^{1/2}$ is evaluated and presented in table 3.

Table 3
Buckling Length factors of the tested columns

Sample No.	P_{cr} (ton)	P_E (ton)	Buckling Factor K
S1	15.5	30.5	1.4
S2	15.5	30.5	1.4
S3	7.7	30.5	1.98
S4	7.7	30.5	1.98
S5	7.4	30.5	2.03

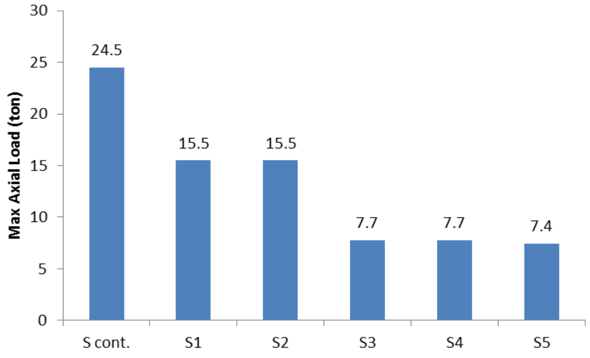


Fig. 23: The critical load of the column in each system

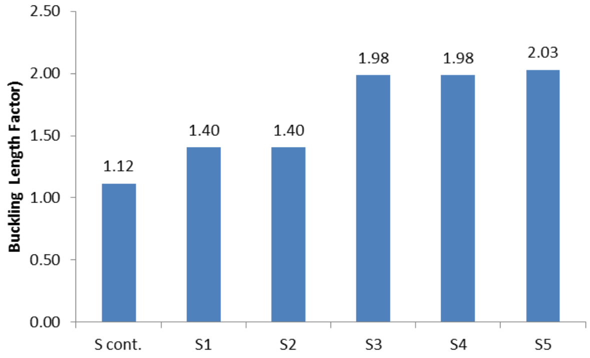


Fig. 24: The buckling length factor of the column in each system

VII. BUCKLING EVALUATION IN ACCORDING TO THE CODES

The buckling loads for the tested columns are re-evaluated using the American Racking Codes which is represented by the Racking Manufacture Institute, RMI 2012. Also, those values are calculated using SCIA software which applies the European Racking Code EN15512. The obtained values with the experimental findings are presented in the next table.

Table 4: Comparison between the calculated and measured critical loads

Loading Pattern	The Critical Load (ton)		
	Experimental	RMI	EN 15512
S1	15.5	10.70	13.55
S2	15.5	10.70	12.97
S3	7.70	10.70	6.82
S4	7.70	10.70	6.53
S5	7.40	10.70	6.63

Studying the previous table, you may find that the results are close to the EN code since that code concerns the second order effect in the analysis.

VIII. SUMMARY AND CONCLUSION

Investigation of the behavior of a perforated columns located in a frame racking system is studied through testing of 5 Full-scale testing frames. The loading location is varied from directly applied on the tested column to the location where the load is applied on all columns. The measured values of the critical loads are used to estimate the buckling length. The outcome of the research is itemized as:

1) Cases of loading S4, and S5 are the most practical cases which are close to the real life application
2) The buckling load factor is found to be 1.4 for both cases S1, and S2 where the load is applied directly on the column or on the column in the short direction.
3) The maximum buckling length factor is found to be 2.03 for tested specimen S5 where the load is applied in eccentric condition. This case is close to the real life application
4) The obtained experimental values of the critical loads are close to the EN 15512 calculation.

REFERENCES

[1] Gregory J. Hancock and Sammy C. W. Lau, "Distortional buckling tests of cold-formed channel sections" (November 8, 1988). International Specialty Conference on Cold-Formed Steel Structures. Paper 3.

[2] Y Pu, M H R Godley, and R G. Beale, "Experimental procedures for stub column tests" (October 15, 1998). International Specialty Conference on Cold-Formed Steel Structures. Paper 2.

[3] Nabil Abdel-Rahman, Ashraf Fadel, Mohamed El-Sadaawy, and Sherif Mourad, "Tests of storage rack channel columns with rear flanges" (October 26, 2006). International Specialty Conference on Cold-Formed Steel Structures. Paper 5.

[4] RMI 2012 “ANSI MH16.1: 2012”, (a revision of MH16.1: 2008), "Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks"

[5] EN 15512 ,(Steel static storage systems - Adjustable pallet racking systems - Principles for structural design".

[6] SCIA Engineer Software Manual

[7] LINKMISR International Company “Manufacturer of Storage Products”, Cairo, Egypt.