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THE BEHAVIOR OF COLD-FORMED BATTENED COLUMNS UNDER LATERAL CYCLIC LOADING

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ملخص :
الهدف الرئيسي من هذا البحث هو دراسة عملية ونظرية لسلوك الاعمدة المكونة من قطاع مشكل على البارد(CFS) تحت تاثير الاحمال المتكررة (cyclic loading).وتم دراسة تاثير نسبة النحافة (slenderness ratio)وسمك الواح التربيط الافقية (thickness of batten plate) والمسافة بين قطاع العمود وايضا المسافة بين الواح التربيط الافقية على سلوك الاعمدة . تم عمل التجارب على عدد ١٥ (خمسة عشر) عمود بالقطاع المشكل على البارد تحت تاثير احمال عمودية محورية واحمال جانبية متزايدة بشكل تكراري (cyclic load). وتم تحليل النتائج ومقارنتها بدراسة نظرية باستخدام طريقة العناصر المحددة (finite element) باستخدام برنامج (ABAQUS), وقد اظهرت المقارنة تقارب في النتائج.

ABSTRACT
The main objective of this research is to investigate experimentally and analytically the cyclic behavior of batten steel column with different slenderness ratios, batten plate thickness, different distance between two longitudinal chords and also different spacing between batten plates. Fifteen batten steel columns subjected to constant axial load and varying cyclic lateral loads had been carried out. An analytical work using the finite element method using the computer program ABAQUS, had been carried out in order to verify the applicability of the method in the prediction of the response. The experimental results showed that, the ultimate failure load for batten steel columns with different batten plate thickness decrease when slenderness ratio decreased by about 13%. The finite element software ABAQUS can be used successfully to simulate the seismic behavior of battens steel columns.
Keywords: Batten steel column; Seismic behavior, Failure load, ABAQUS, Displacement.

INTRODUCTION
A built-up battened column is a kind of compression member consisting of two or more identical longitudinal chords that are connected to each other by batten plate at different spacing along their length. These longitudinal chords are usually used as light-weight compression elements, such as steel columns in steel structures. Double-channel sections are usually used as battened column. The average thicknesses of cold-formed steel are regularly with scopes between 0.40mm to 6.00mm [1]. Based on the AISI specification [2], the yield stress for the virgin steel that is used for cold-formed sections is usually ranging from 165MPa to 552MPa.

El Aghoury et al. [3] mentioned that Cold-formed steel structural elements play a great role in new steel structures because of their high strength and light weight. The strength and performance of battened column elements collected of slender angle sections are mainly governed by local buckling of angle chords or torsional buckling of the angle between batten plates. Additionally, local buckling based on the interaction between the width– thickness ratio of angle chords, overall slenderness ratio of angle between batten plates and overall slenderness of column.

Mohamed et al. [4] showed a tested investigation on performance and design of built-up cold-formed steel section battened columns. The built-up columns were pin-ended and involved two cold-formed steel channels located back-to-back at different spacing of intersection. The cold-formed steel channel sections were manufactured by brake-pressing flat strips having a plate thickness of 2 mm. The built-up cold-formed steel section battened columns had different slenderness and geometries but had the same nominal length of 2,200 mm.

Behrokh and Mohammad [5] performed a tested study for batten columns exposed to combination of constant axial compression and inverted cyclic lateral loads to calculate their cyclic response, obtainable ductility and post failure behavior below seismic conditions. To decide and estimation the obtainable ductility of batten columns, the backbone curves have been developed using experimental hysteresis curves of columns. The influence of diverse parameters such as axial compression, distance between battens and distance between chords on the obtainable ductility of batten columns have further been studied. Outcomes reveal that the available ductility of batten columns is significantly low equated with solid web columns.

Bonab et al. [6] develop the static performance of laced columns, 18 tests were performed on sample columns constructed from pairs of u-section profiles with different lengths and different distances between the main legs, all with a primary inadequacy. To discuss the performance of built-up columns in the plane parallel to the lacing planes, the experiment set-up was organized in such a way that buckling happened in this plane. There was generally good arrangement between the test outcomes and the theoretical results for the elastic critical loads.

Diptiranjan and Durgesh [7]. the investigations showed that under constant axial load and varying cyclic lateral loads, specimens with conventional design arrangement failed to reach its full plastic moment capacity of section prior to failure because of variability. The different designed specimens presented excellent performance in expressions of moment rotation response, flexural strength and stiffness, ductility and energy dissipation capacity as equated to specimen designed as per current code specifications.

EXPERIMENTAL EVALUATION

Test Specimens Description

The test program included fifteen full-scale batten steel columns as shown in Figure 1 While Table 1 summarizes the different properties of the tested batten steel columns. Which can be divide in some group according to effect of parameter such as; group one length of chords(C1,C6,C11)(C2,C7,C12)(C3,C8,C13)(C4,C9,C14)(C5,C10,C15), group two spacing between batten plate (C2,C4)(C7,C9)(C12,C14) and group three batten plate thickness (C1,C2,C3)(C6,C7,C8)(C11,C12,C13). The cross section dimensions of batten steel columns web height, flange width and their thickness equal to 140.0 mm, 65.0 mm and 4mm, respectively. The width of batten plates equal to 100.0 mm for all tested steel columns. The yield stresses of channel sections and plates were 360MPa. The cyclic lateral loading was applied at the top of tested batten steel columns.

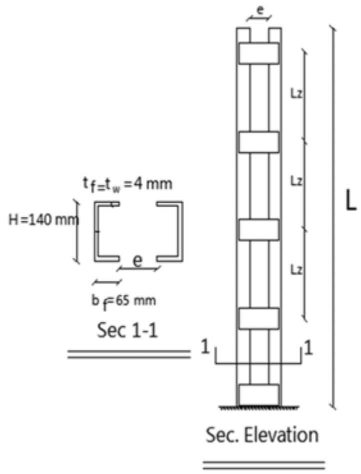


Fig. (1): Details of typical specimen.

Table (1): Different properties of tested batten steel columns

Steel column	Column height (L), mm	Thickness of batten plate (t b), mm	Spacing between batten plate c/c (L z), mm	Clear spacing between two flange of column(e) , mm
C1	1800.0	2.0	420.0	100.0
C2	1800.0	4.0	420.0	100.0
C3	1800.0	6.0	420.0	100.0
C4	1800.0	4.0	320.0	100.0
C5	1800.0	4.0	420.0	300.0
C6	1400.0	2.0	420.0	100.0
C7	1400.0	4.0	420.0	100.0
C8	1400.0	6.0	420.0	100.0
C9	1400.0	4.0	320.0	100.0
C10	1400.0	4.0	420.0	300.0
C11	1000.0	2.0	420.0	100.0
C12	1000.0	4.0	420.0	100.0
C13	1000.0	6.0	420.0	100.0
C14	1000.0	4.0	320.0	100.0
C15	1000.0	4.0	420.0	300.0

2.2 Test Parameters

In this study, four parameters have been investigated. These parameters are the length of steel columns, thickness of batten plate, spacing between batten plate, and clear distance between two chords. A total of fifteen batten steel columns (C1 to C15) were tested.

2.3 Experimental Setup and Instrumentation

Figure 2 illustrates the steel test setup and schematic view for batten steel columns with different slenderness ratios. The steel setup includes two main parts: the main frame and the specimen supporting system. The main frame consists of two vertical steel columns of (S.I.B # 400) that are connected together by two beams (channel # 260). The two beams are fixed on the vertical steel column by eight bolts M16 for each beam. Horizontal two-way hydraulic jack of 1000 KN capacity is fixed on the steel column of the main frame.

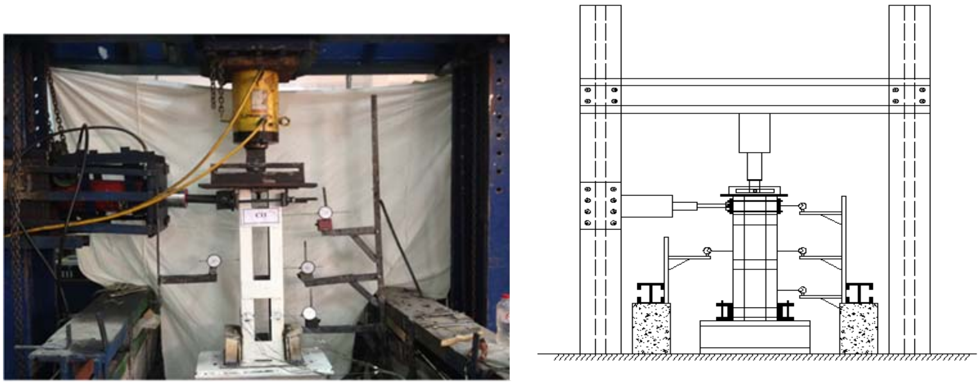


Fig. (2): Test setup and schematic view of batten steel column

2.4 Load History and Instrumentation

Each batten steel column was tested under cyclic loading in a predetermined load and displacement sequence. Two-way digital hydraulic jack of 1000 KN capacity was used to apply the forward and reverse loading at the top of the column. The base of the column was fixed and the top was loaded. The total superimposed vertical load on the column was 20.0 KN. Electrical resistance 6mm length strain was used to measure the strains at the critical locations of the batten steel columns. Linear Variable Differential Transformer (LVDT) and dial gauges were used to measure the displacement at the top, mid and bottom height of the column.

Load History

The tested batten steel columns were subjected to quasi-static cyclic loading simulating earthquake loads. The history of the lateral load and lateral displacement sequence used in the tests of batten steel columns is illustrated in Fig. 3

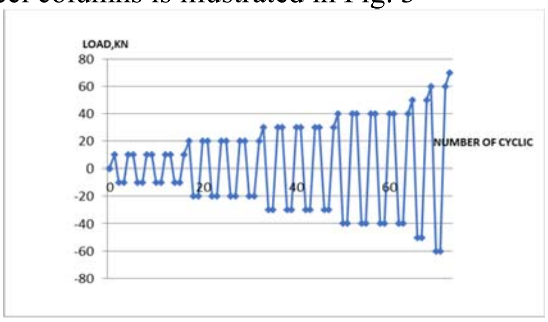


Fig. (3): Load sequence diagram

EXPERMENTAL RESULTS

3.1 Failure Load

The experimental failure loads of tested steel column are shown in Table 2. The ultimate failure load for batten steel columns, increase with increased the plate thickness, decrease with increased the batten plate spacing and also decrease with increased spacing between two chords.

Table (2): Observed failure load of tested steel columns.

Tested column	Failure load, KN	Tested column	Failure load, KN
C1	47.50	C9	62.50
C2	70.00	C10	50.00
C3	72.50	C11	42.50
C4	62.50	C12	65.00
C5	50.00	C13	67.50
C6	47.50	C14	70.00
C7	57.50	C15	50.00
C8	60.00		

3.2 Top Column Displacement

Experimentally, maximum top column displacement of steel columns is shown in Table 3. The maximum top column displacement of steel column increase with increased thickness of batten plates, as well increase with increased batten plate spacing and decrease with increased spacing between two chords.

Table (3): The recorded maximum top displacement of steel columns.

Tested column	Maximum displacement, mm	Tested column	Maximum displacement, mm
C1	58.57	C9	83
C2	90.00	C10	30.71
C3	108.20	C11	40.6
C4	97.35	C12	57.96
C5	57.26	C13	54.15
C6	53.1	C14	46.10
C7	56.44	C15	35.45
C8	62.38		

3.3 Hysteretic Curve of Lateral Cyclic Load Versus Column

Figures 4 to 18 show the hysteretic curves of lateral load versus top displacement of the column for all tested specimens. The lateral stiffness of batten steel column increase with batten plate thickness increased, when the batten plate spacing increased the lateral stiffness of batten steel column decreased, and lateral stiffness decrease with increased of spacing between two chords.

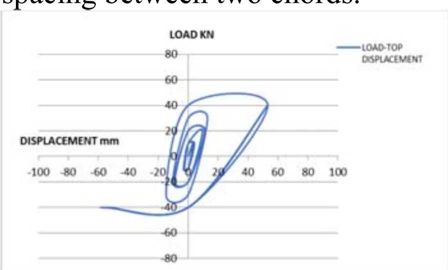


Fig. (4): Hysteretic loop of C1

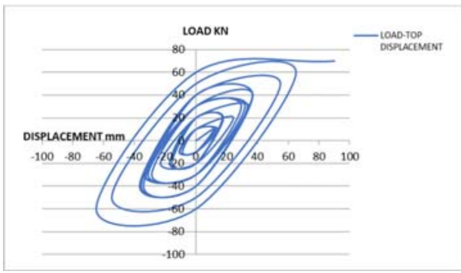


Fig. (5): Hysteretic loop of C2

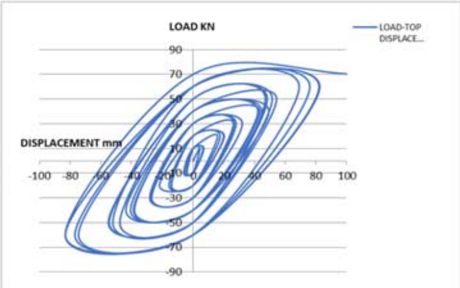


Fig. (6): Hysteretic loop of C3

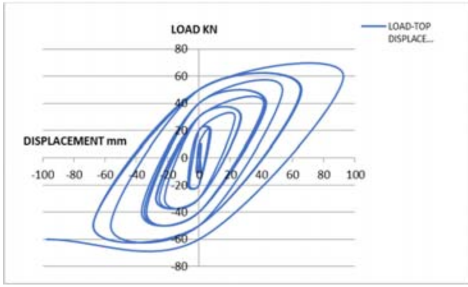


Fig. (7): Hysteretic loop of C4

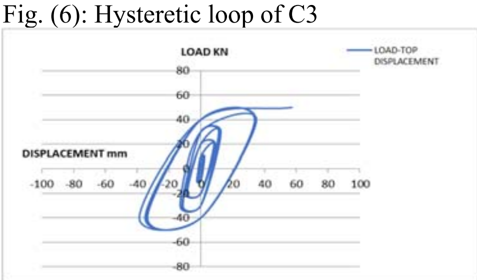


Fig. (8): Hysteretic loop of C5

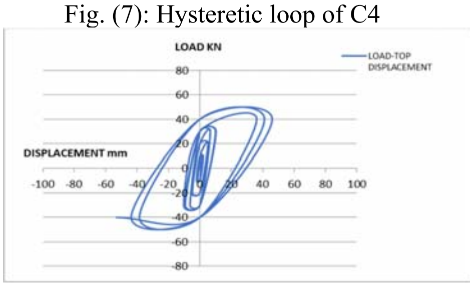


Fig. (9): Hysteretic loop of C6

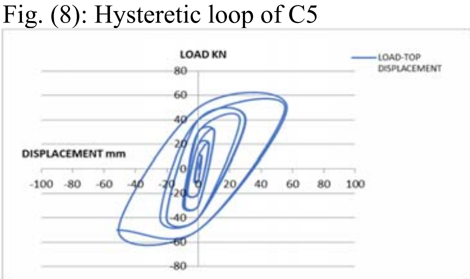


Fig. (10): Hysteretic loop of C7

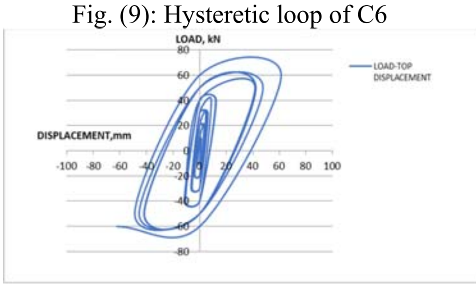


Fig. (11): Hysteretic loop of C8

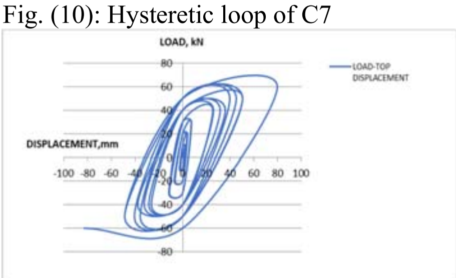


Fig. (12): Hysteretic loop of C9

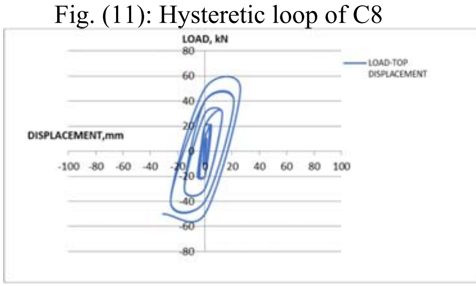


Fig. (13): Hysteretic loop of C10

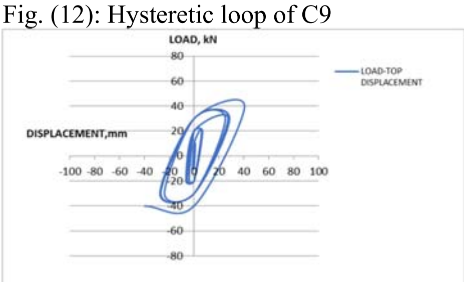


Fig. (14): Hysteretic loop of C11

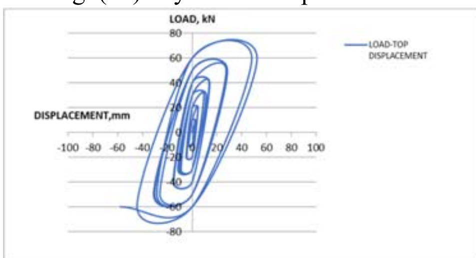


Fig. (15): Hysteretic loop of C12

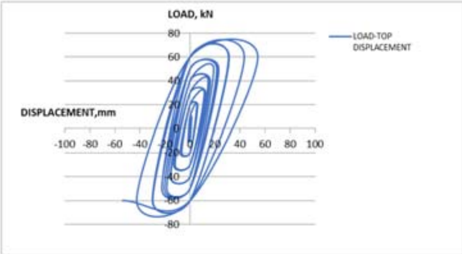


Fig. (16): Hysteretic loop of C13

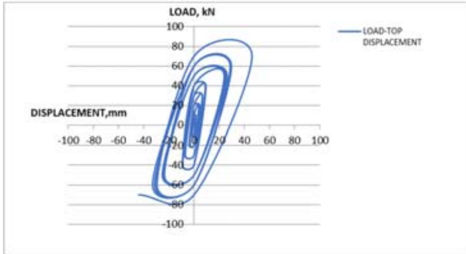


Fig. (17): Hysteretic loop of C14

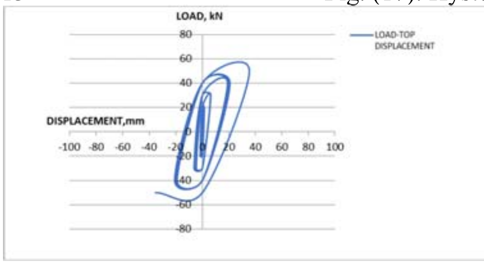


Fig. (18): Hysteretic loop of C15

3.4 Displacement Ductility Factor (μ)

The displacement ductility factors of all the tested batten steel columns are given in Table 4. The displacement ductility factor for batten steel column with different in batten plate thickness decrease with increased slenderness ratio, also the same result obtain from batten steel column with different in distance between batten plate and longitudinal chords.

Table (4): The displacement ductility factor of all steel columns.

Tested column	Displacement ductility factor, μ	Tested column	Displacement ductility factor, μ
C1	4.55	C9	11.37
C2	2.69	C10	8.72
C3	3.37	C11	6.66
C4	3.83	C12	5.88
C5	4.88	C13	4.29
C6	8.41	C14	5.12
C7	6.04	C15	7.45
C8	7.10		

3.5 Failure Mode

The test is performed on the column specimen until the excessive loss in lateral strength is observed. During the tests, the failure of specimens is initiated in the form of buckling or yielding in the longitudinal chords or batten plate of specimens. The observed failure is due to the axial compression and bending moment which is imposed onto the chords during lateral loading of specimens. The buckling of the chords is occurred symmetrically about the central axis of the column, the failure mode of all tested steel columns is presented in Fig. 19 to 33.

Fig. (19): Failure mode of C1in (batten plate)

Fig. (20): Failure mode of C2 (bottom)

Fig. (21): Failure mode of C3 in (bottom)

Fig. (22): Failure mode of C4 in (bottom)

Fig. (23): Failure mode of C5 in (batten plate)

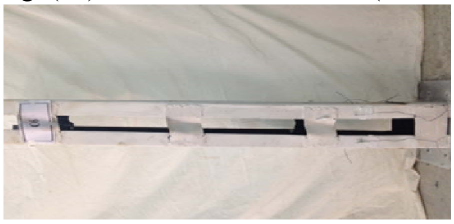


Fig. (24) Failure mode of C6 in (batten plate)

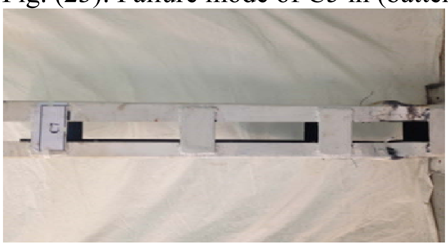


Fig. (25): Failure mode of C7 in (bottom)

Fig. (26): Failure mode of C8 in (bottom)

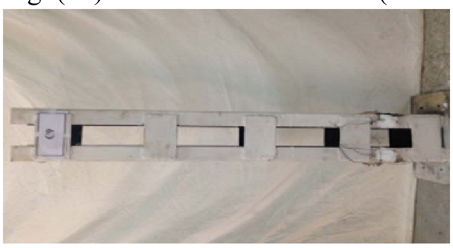


Fig. (27): Failure mode of C9 in (bottom)

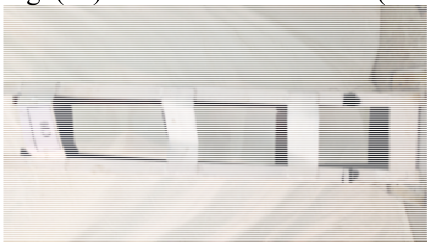


Fig. (28): Failure mode of C10 in (batten plate)

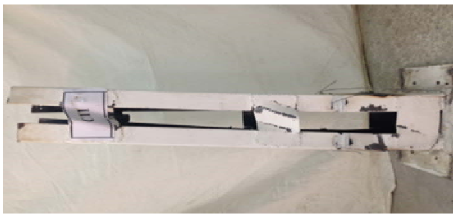


Fig. (29): Failure mode of C11 in (batten plate)

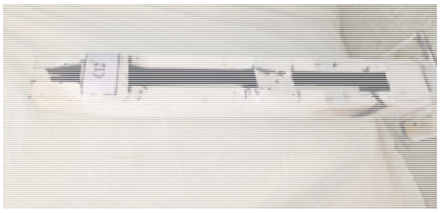


Fig. (30): Failure mode of C12 in (bottom)

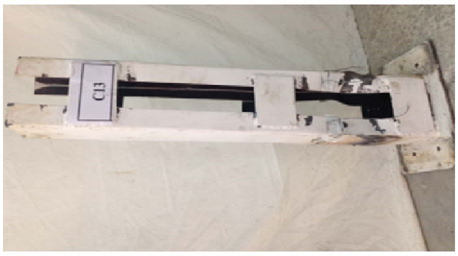


Fig. (31): Failure mode of C13 in (bottom)

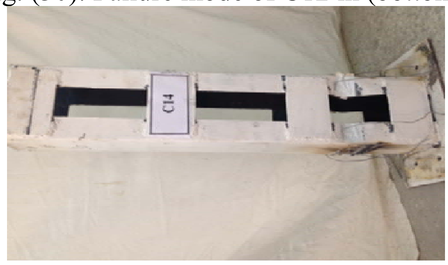


Fig. (32): Failure mode of C14 in (bottom)

Fig. (33): Failure mode of C15 in (batten plate)

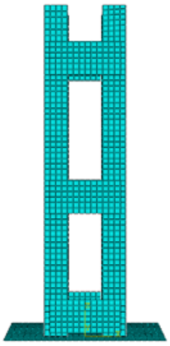
ANALYTICAL EVALUATION

Finite element models may offer more accurate analyses because of the ability to model in details the material and interaction of each part of the system. In this method, element and material model types play an important role for the analysis is based on the structural system and specific need or emphasis of the study.

In this study, a three dimensional analysis of batten steel columns is carried out. The analysis is performed using the finite element software ABAQUS [9] with adopting the plasticity model, is presented. The obtained numerical results of the batten steel columns under reversed loading are compared with the measured results of the experimental program.

4.1 Finite Element Mesh

After selecting the used element types, meshing the model to transform geometric modeling to finite element model (FEM) as (nodes and elements). Through this operation the assigning of every section property and element type has to be done. In order to obtain accurate results from the finite element model, all the elements in the model were purposely assigned the same mesh size; the mesh elements of shell with size 20*20mm. Figs. 34 and 35 illustrate steel meshes of some batten steel columns.



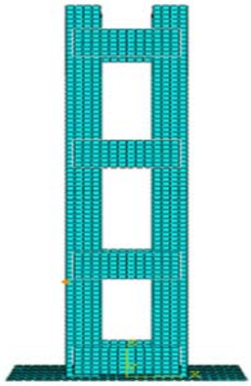


Fig (34): Meshes of batten column C12.   Fig (35): Meshes of batten column C14

4.2 Boundary Conditions

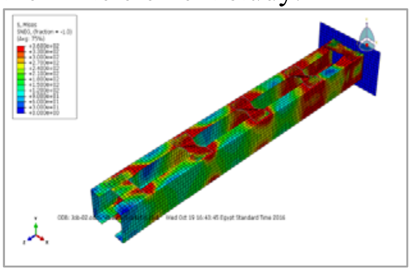
Loading and boundary conditions were performed in the model of batten steel columns to simulate the experimental test setup, for some studied batten steel columns. The bottoms of batten steel columns were fixed and the top of the upper columns was loaded by reversed loading. The batten steel columns were subjected to quasi-static cyclic loading simulating an earthquake load.

4.3 Material Modeling and Properties

Two material behaviors is linear elastic with young's modulus 210GPa, poison ratio of 0.30. The experimental yield strength of the used steel is equal to 360Mpa. The tangent modulus for the second segment is takes 2Gpa. In all plastic analysis cases, the Von-Misses yield criterion is used with the associated flow rule. Kinematics hardening is used for the case of cyclic analysis to take the effect of strain hardening.

4.4 Mode of Failure

The mode of failure of battened member as observed in finite element studies is shown in Figs 36 to 50. The local buckling in form of depression in the webs and bulging of flanges of battened member was observed in the panel near the fixed end. The mode of failure of battened members observed in the experimental study matched very well with the finite element study.



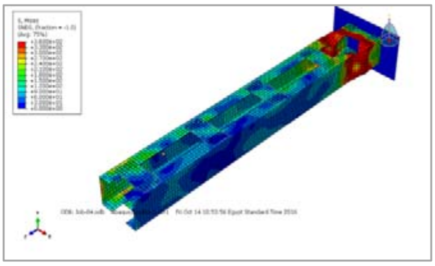


Fig (36): Failure mode of (FEM) C1   Fig (37): Failure mode of (FEM) C2

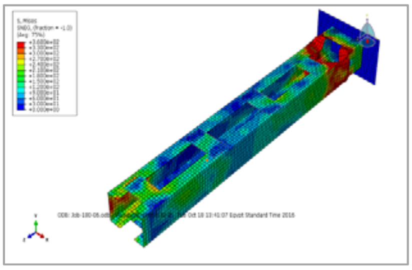


Fig (38): Failure mode of (FEM) C3

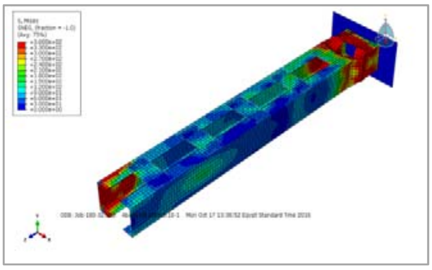


Fig (39): Failure mode of (FEM) C4

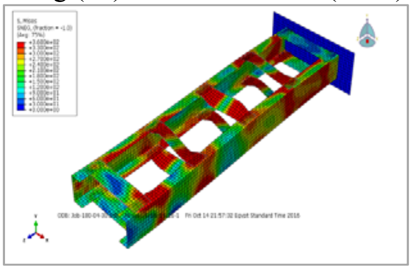


Fig (40): Failure mode of (FEM) C5

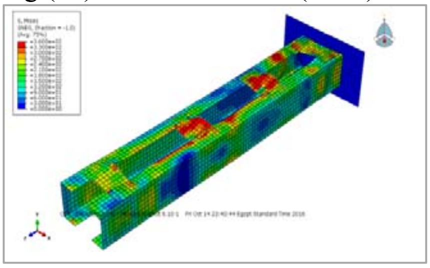


Fig (41): Failure mode of (FEM) C6

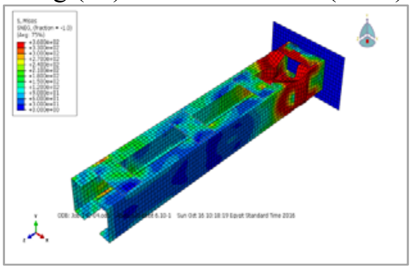


Fig (42): Failure mode of (FEM) C7

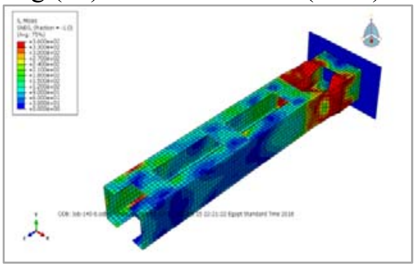


Fig (43): Failure mode of (FEM) C8

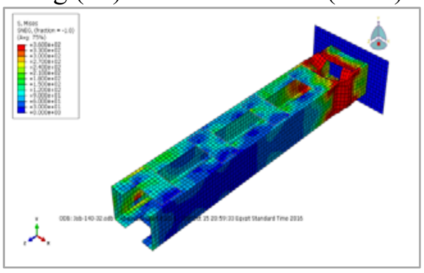


Fig (44): Failure mode of (FEM) C9

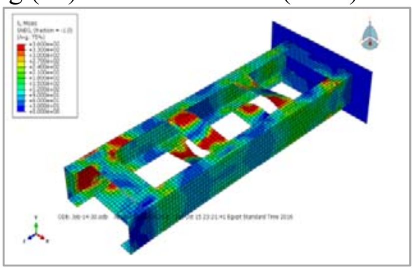


Fig (45): Failure mode of (FEM) C10

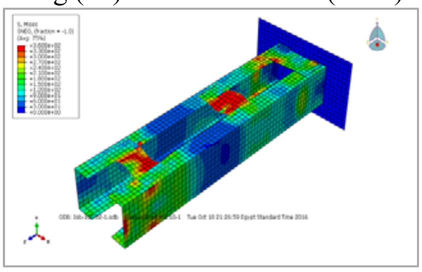


Fig (46): Failure mode of (FEM) C11

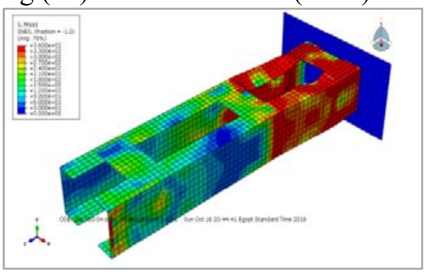


Fig (47): Failure mode of (FEM) C12

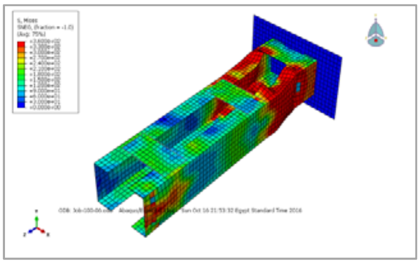


Fig (48): Failure mode of (FEM) C13

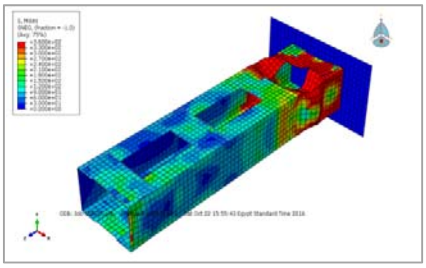


Fig (49): Failure mode of (FEM) C14

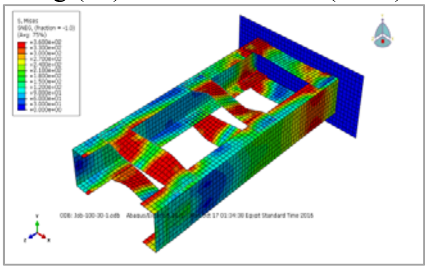


Fig (50): Failure mode of battened column C15

5 COMPARISONS BETWEEN FINTE ELEMENT RESULTS AND THE EXPERMENTAL RESULTS OF TEST BATTEN COLUMNS

5.1 Failure Load

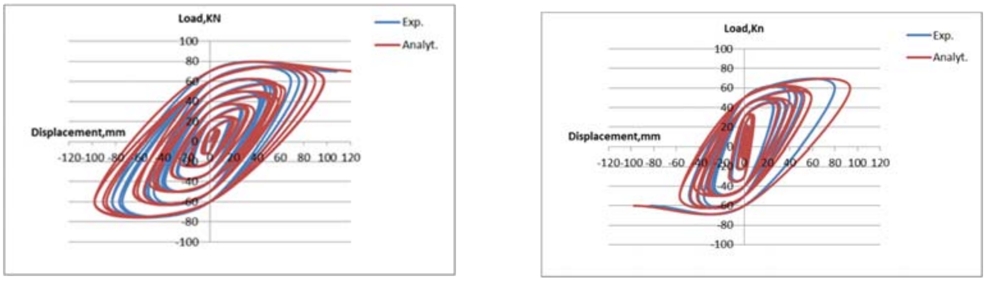
Table 5 shows a comparison between experimental values of peak lateral load of batten steel columns and that calculated from the finite element analysis. These results show that, the finite element ABAQUS predicts the ultimate load with low accuracy because stiffness degradation in the finite element analysis is less than that obtained from experimental results.

Table (5): Comparison between the experimental values of failure load and that calculated from finite element method.

Tested column	EXP./ Analytical	Tested column	EXP./ Analytical
C1	0.913	C9	0.919
C2	0.921	C10	0.909
C3	0.929	C11	0.924
C4	0.933	C12	0.903
C5	0.926	C13	0.912
C6	0.880	C14	0.897
C7	0.898	C15	0.926
C8	0.909		

5.2 Hysteretic Curves of Lateral Cyclic Load Versus Column Displacement

The comparison between the experimental values of maximum displacement at the top of the column for batten steel columns and that calculated from the finite element are showed in Table 6. The comparison indicates that in all slenderness ratio difference between the theoretical and experimental value of maximum displacement at the top of the columns is about 14.80%. Figs 13 to 15 illustrate some comparison between the hysteretic loop of batten steel columns in experimental and finite element. These results show that, the experimental displacement at the top of the column differs from that calculated by finite element analysis because the bottom fixed base of batten steel columns is well done by using finite element program ABAQUS.



(b)

Fig. (51): Comparison between experimental hysteretic loop of column (a) C4, (b) C9 and that calculated from FE

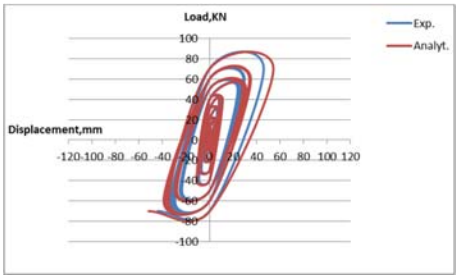


Fig. (52): Comparison between experimental hysteretic loop of column C14 and that calculated from FE.

Table (6) Comparison between the experimental values of top column displacement and that calculated from finite element method.

Tested column	EXP./ Analytical	Tested column	EXP./ Analytical
C1	0.852	C9	0.852
C2	0.894	C10	0.906
C3	0.849	C11	0.853
C4	0.852	C12	0.853
C5	0.903	C13	0.853
C6	0.866	C14	0.854
C7	0.867	C15	0.805
C8	0.903		

CONCLUSIONS

Based on the results obtained from this investigation on the seismic behavior of batten steel columns, the following conclusions can be drawn:

The ultimate failure load for batten steel columns, increase with increased the plate thickness, decrease with increased the batten plate spacing and also decrease with increased spacing between two chords.

The maximum top column displacement of steel column increase with increased thickness of batten plates, as well increase with increased batten plate spacing and decrease with increased spacing between two chords.

The lateral stiffness of batten steel column increase with batten plate thickness increased, when the batten plate spacing increased the lateral stiffness of batten steel column decreased, and lateral stiffness decrease with increased of spacing between two chords.
The displacement ductility factor for batten steel column with different in batten plate thickness decrease with increased slenderness ratio, also the same result obtain from batten steel column with different in distance between batten plate and longitudinal chords.

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