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Research Article

Enhancing Torsional Behavior of Cold Formed Square Hollow Steel Columns by Carbon Fiber Reinforced Polymer

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Abstract: The aim of this research is to enhance the torsional behavior of Square Hollow Steel (SHS) columns in existing structure through strengthening by Carbon Fiber Reinforced Polymer (CFRP). An appropriate modeling using the finite element software [ANSYS 14.5] is carried out to investigate the torsional behavior of strengthened steel Square Hollow Sections (SHS) with various thicknesses and calculate angles of twist. Analysis results showed a significant reduction in angles of twist for thin-walled sections after strengthening. The amount of increase in the maximum torsional capacity is related to the thickness of the original section. Thin-walled sections with large depth to thickness ratio (high D/t ratio) showed a larger improvement compared with the thicker-walled sections with low depth to thickness ratio (low D/t ratio) in the terms of maximum torsional capacity. The proposed numerical model is used in strengthening cold formed inclined columns of existing tents under the action of inclined forces and torsion. The strengthened model section capability against local buckling and twist is enhanced 64%.

Keywords: Buckling behavior, CFRP strengthened, cold-formed steel, finite element, square hollow sections, Thin-walled and torsional load

INTRODUCTION

The structural applications of Square Hollow Section (SHS), became widespread in the world during the past few decades because of the many advantages that can be gained from using it such as lower weight, high resistance, large load carrying capacity, ability to resist torsion, high ductility of steel as well as economic terms. On the other hand, some tubular cold formed structures, exposed to severe environment often suffer a state of deterioration and rust and others need to be rehabilitated and strengthened due to excessive loads. Therefore, there is a need to look for the technologies used to sustain these structures. Previously, investigators used steel plates for external strengthening. This method is practically considered successful but, it has many disadvantages such as, tough in shaping, heavyweight which requires large equipment for lifting and difficulty in installation especially in the complex cutting. In addition, this manner of using the steel plates is susceptible to corrosion due to rust which increases the cost of maintenance later. In contrast, strengthening of structures by using Carbon Fiber Reinforced Polymer (CFRP) composites did not show any of these defects mentioned above (Sundarraja *et al*., 2014).

In civil engineering, strengthening and rehabilitation of steel structures was one of the important challenges during the past decades. Use of (FRP) compounds for this purpose has become widespread and overcome many difficulties facing these structures. Many researchers employed the use of CFRP for strengthening thin-walled steel structures as tensile strengthening, flexural strengthening, strengthening stability of the steel section, repair of fatigue damages and improvement fatigue life (Ashvini and Subramanian, 2015). But a few used strengthening for enhancing torsional capacity of the steel hollow sections. Therefore, strengthening with CFRP will be used to enhance the torsional capacity of cold formed steel hollow columns subjected to load combinations including torsional effects.

LITERATURE REVIEW

Previous studies on strengthening hollow sections with CFRP wrapping with an angle of 45° showed how it is the most effective in terms of increasing torsional capacity (Wang *et al*., 2013). In addition to this, Chahkand *et al*. (2013) carried out four different wrapping configurations and found that the best orientation angle for fibers is in the same direction as the principal tensile stress produced from torsion. When a member is subjected to pure torsional moment, normal stresses are negligible in longitudinal and transverse directions of the member. The shear stresses

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Table 1: Dimension and properties of columns

Materials	Dimension (mm)	Length (mm)	Elastic modulus GPa	Yield strength MPa
Steel	100×100×2	460	202	383
	100×100×3	460	201	434
	300×300×6	3200	201	444
CFRP			230	4900

Fig. 1: Torsion testing apparatus (Sharrock *et al*., 2015)

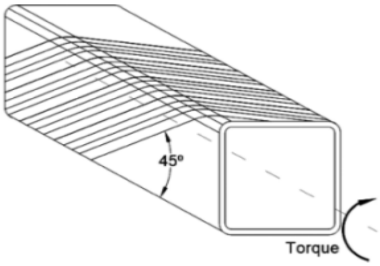


Fig. 2: Strengthening method (Sharrock *et al*., 2015)

will cause principal stresses and will be greatest in direction ±45° with respect to the longitudinal axis of the member (Sharrock *et al*., 2015).

MATERIALS AND METHODS

The validity and accuracy of the adopted finite element models will be studied and checked by analyzing SHS previously tested experimentally by Sharrock *et al*. (2015). Figure 1 shows the tested specimens in the experimental program. A study on the torsional behavior for a number of models strengthened with four layers of CFRP, each layer being wrapped at a 45° spiral wrapping direction was carried out leading the CFRP to work in tension as shown in Fig. 2.

The testing program on cold-formed steel Square Hollow Sections (SHS) with or without CFRP wrapping included two SHS specimens with dimensions of (100×100×2) mm and (100×100×3) mm and symbolized as SC-2 and SC-3 respectively for the steel control specimens and SW-2 and SW-3 for steel specimens with CFRP wrapping. The material properties and dimensions are presented in Table 1.

Columns FE modelling: Since the problem under investigation is of highly nonlinear nature with no closed form solution available, numerical analysis will be conducted. The nonlinear finite element analysis of structural members has been widely used in recent years. It is a powerful numerical tool which can be used to predict the structural behavior in the entire load range up to failure and study the effects of different parameters on the structural behavior. ANSYS 14.5 software is used in this research to simulate the behavior of torsion of SHS non-strengthened and strengthened by CFRP. Generally, cold formed thin walled SHS members include relatively thin webs, when subjected to loading through their width, undergo for deformations. Since, these members have large width-to-thickness ratios, the shell element is often used to represent thin walled structures and supply more carful results with a sensible analysis time compared to volume elements (MacDonald and Kulatunga, 2013). Herein, SHELL181 element is used to represent the steel. This element has been successfully used in three dimensional nonlinear SHS analysis. SHELL181 element is defined by shell section information with four nodes at corners (Fig. 3). The 3-D SHELL41 element is used to model CFRP sheets. The element has 4-nodes as shown in Fig. 4 and has membrane stiffness (in-plane) but, have no bending stiffness in the out-of-plane direction. It is suitable for shell structures when bending of the elements are of secondary significance.

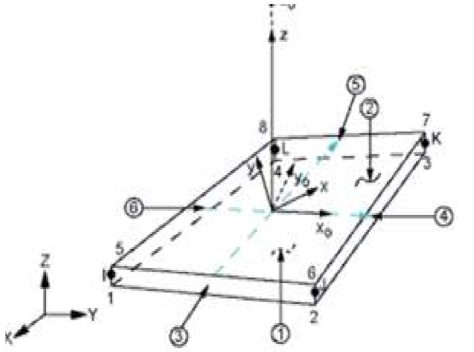


Fig. 3: SHELL181 geometry (ANSYS 2014.5)

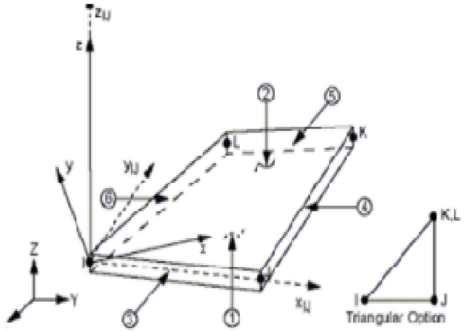


Fig. 4: SHELL41 geometry (ANSYS 2014.5)

Fig. 5a: Mesh of columns SC & SW

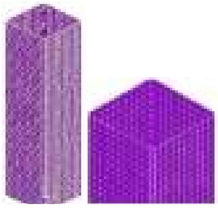


Fig. 5b: CFRP representation of columns SW

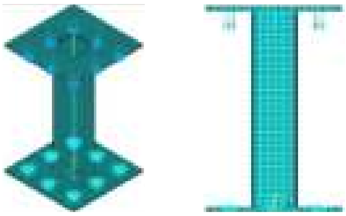
Verification of the FE model: The following steps are chosen to model and mesh all the tested columns:

Step 1: The steel is modeled using shell elements of dimensions (100×100×2) mm and (100×100×3) mm. Both specimens' ends are fixed with plates of dimensions (300×300×12) mm. Thickness of all steel sections is modeled using two layers of shells: 1 mm for each layer for column with 2 mm thickness, 1.5 mm for each layer for column with 3 mm thickness and 6 mm layer thickness for each layer of the end plates with 12 mm total thickness.

Step 2: The structure is meshed and then divided into (10×10) mm with total (3471) elements connected together at their nodes with various thicknesses as shown in Fig. 5a.

Step 3: Representation of CFRP for specimens SW as shown in Fig. 5b. These sheets are executed by using the existing nodes of steel column. Thus no meshing process is required for the CFRP layers. Meshing of CFRP is designed using triangular elements due to the use of large deformation effects option. The number of CFRP elements reached to (4048).

Displacement boundary conditions are needed to constrain the model for good solution. To ensure that the model acts the same way as the experimental specimen, the boundary conditions need to be applied at some points of symmetry where the supports to be put as those in the experimental work. For the numerical procedure, the support, worked at the lower plate in the same place where the bolts are fixed as indicated in Fig. 6a. 72-nodes are chosen spread over 8 places, each 9 nodes representing one bolt and constrained in the X, Y and Z directions (UX = UY = UZ = 0) only. The applied load is performed as a moment applied at the upper plate in the same place where the bolts are fixed. It is chosen as the 72-nodes spread over 8 places, each 9 nodes representing one bolt having an applied moment about Y-axis as shown in Fig. 6b. The small moment for each node on the edge of plate is calculated and chosen to represent the torque-angle of twist curve.



(a) (b)

Fig. 6: Boundary conditions at lower plate and torsional loading at upper plate for SC & SW

Type of analysis: The modified Newton-Raphson method is used for the solution of the nonlinear equations in the finite element analysis to investigate the maximum torsional capacity of column specimens and torque-angle of twist results. The application of the loads up to failure is done incrementally as required by the Newton-Raphson procedure. Therefore, the total applied load is divided into a series of load increments (load steps). At certain stages in the analysis, load step size is varied from large (at points of linearity in the response) to small (when steel yielding occurs). Torque vs angle of twist curves for all specimens are presented for each thickness of tubular steel section. Program ANSYS can obtain the torque-angle of twist curves directly, because SHELL181 element has six degree of freedom solution (UX, UY, UZ, ROTX, ROTY and ROTZ). The calculation of the angle of twist is carried out through the nodes at the edge of the upper plate.

RESULTS AND DISCUSSION

The finite element results are compared with experimental results data as shown in Fig. 7 to 12.

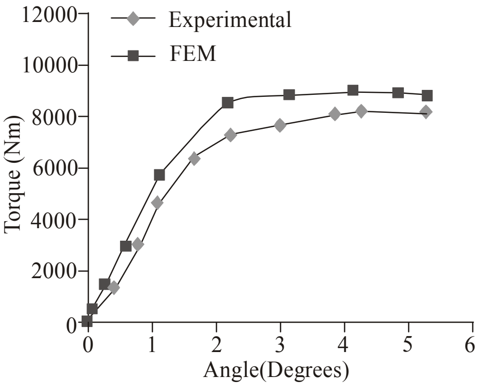


Fig. 7: Experimental and FEM output for 2mm hollow section without CFRP (SC-2)

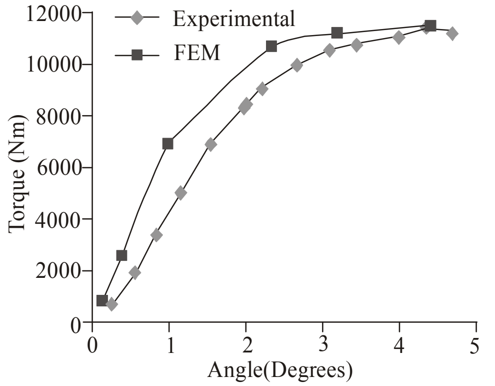
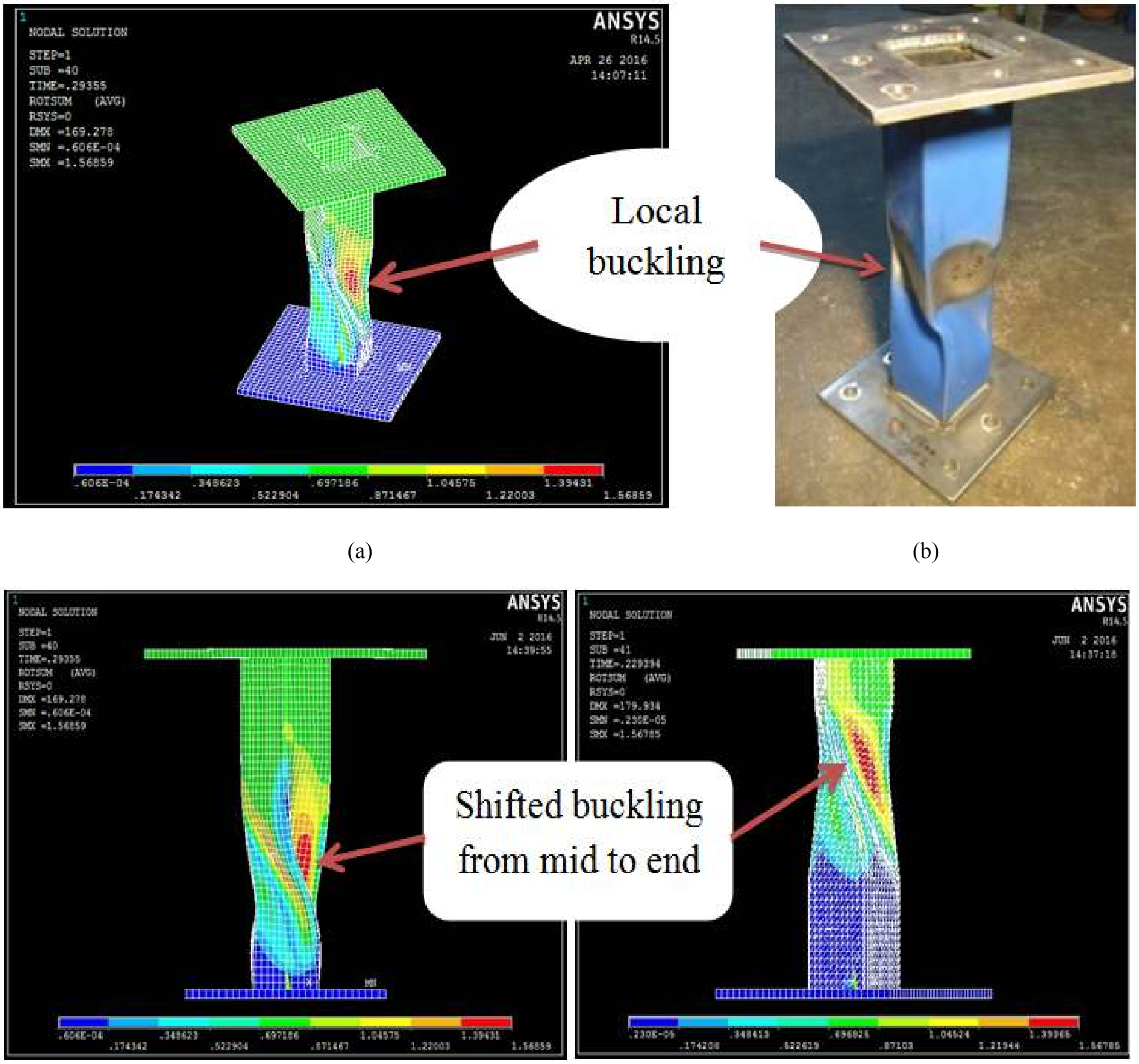


Fig. 8: Experimental and FEM output for 2 mm hollow section with CFRP (SW-2)

Table 2 shows the experimental and FEM ultimate torque capacity and the rotation angle at the maximum torque for SC-2, SC-3, SW-2 and SW-3. Also, the ratio between the FEM to experimental maximum torque capacity and angle of rotation is presented.

The difference between FEM failure torque and experimental failure torque ranges from (1-10)% and the difference between FEM and experimental rotation at failure torque varied from (1-3)% for the SHS strengthened by CFRP. From the results shown in Table 2, it can be concluded clearly that the ultimate torsional capacity and rotations obtained from Finite Element Method (FEM) work is in good agreement with the results obtained from the experimental work. The deformed shapes showing the results of vector



(a)

(b)

(c)

(d)

Fig. 9: (a): FE model shape; (b): Experimental failure shape (Sharrock *et al*., 2015); (c): Buckling without CFRP; (d): Buckling with CFRP

Table 2: Comparison between EXP and FEM ultimate torque capacity and rotation of SHS with and without CFRP wrapping

Section name	Maximum torsional capacity (Nm) EXP	FEM	FEM/EXP %	Rotation angle at maximum torque (degree) EXP	FEM	FEM/EXP %
SC-2	8145	8934.34	90	4.27	4.157	97
SC-3	15280	15273.16	99	9.22	9.18	99
SW-2	11202	11291.77	98	4.34	4.24	98
SW-3	17638	18412	95	7.11	7.22	98

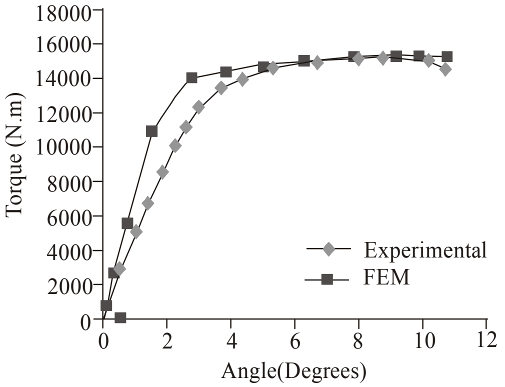


Fig. 10: Experimental and FEM work for 3mm hollow section without CFRP (SC-3)

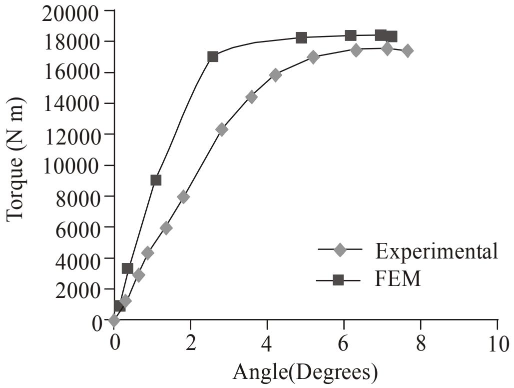
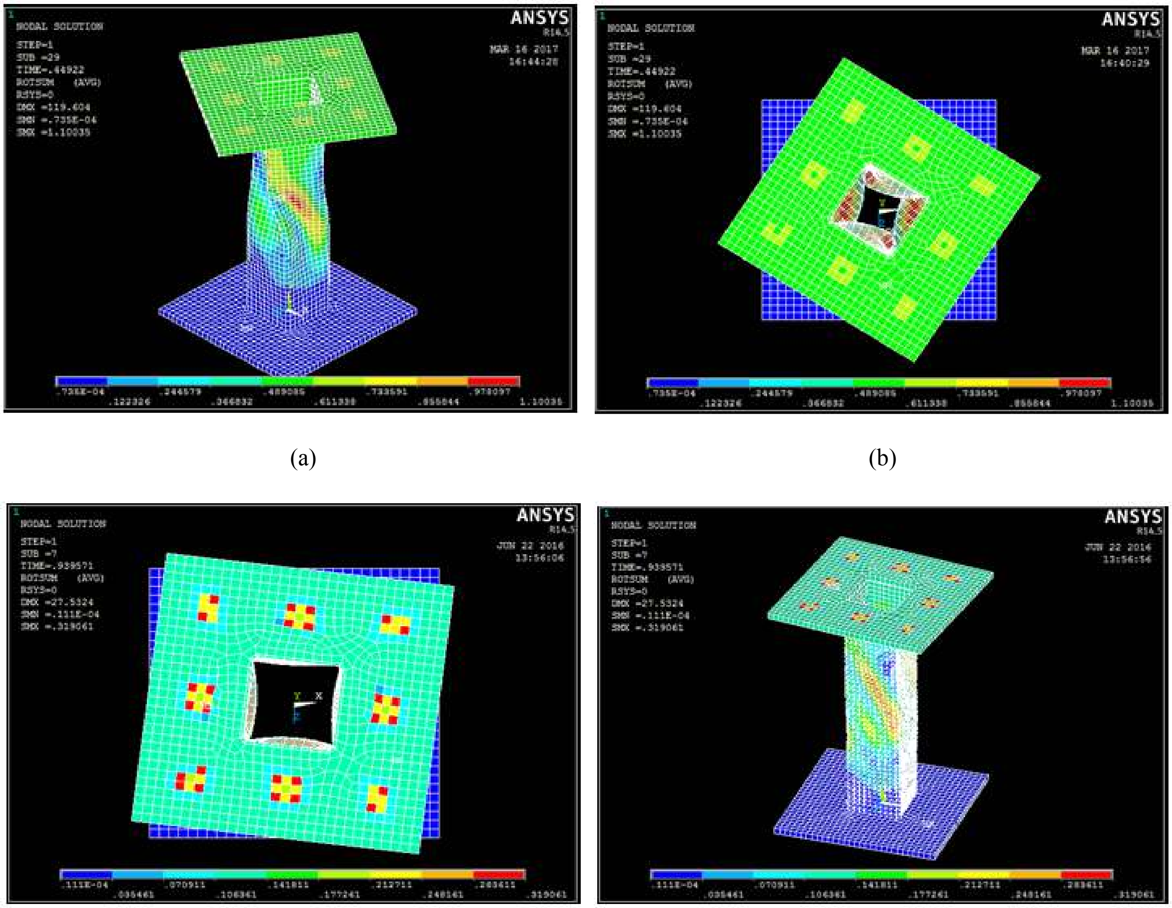


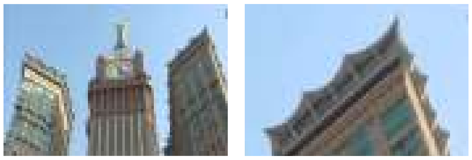
Fig. 11: Experimental and FEM work for 3mm hollow section with CFRP (SW-3)



(a) (b)

(c) (d)

Fig. 12: (a) And (b) Buckling and rotation values without CFRP wrapping (c) and (d) Buckling and rotation values with CFRP wrapping



(a) (b)

Fig. 13: The columns supporting the tents at the roof of Abraj Al-Kalaa

summation of rotations for all specimens shown in the previous Figures can give the following observations:

- Because all sections have the same outer diameter, it allows comparing the D/t ratios. According to the classical theory, increasing of steel thickness will increase torsional capacity for non-strengthened sections (Murray, 1984). Therefore, thin-walled sections with higher D/t ratio will have more benefit due to CFRP bonded on the exterior surfaces. The maximum torsional capacity for all strengthened models is larger than their control pair. In thin-walled sections the enhancement was large, mainly for the 2 mm steel section which gives 26% enhancement on the maximum torsional capacity. The 3 mm steel section revealed an improvement of 20% on the maximum torsional capacity. This is sure since a higher D/t ratio will make the CFRP wrapping more efficient and will verify the increase in maximum torsional capacity.
- When strengthening the steel sections with CFRP, local buckling moved from the middle section to the upper end as shown in Fig. 9c and 9d. But when a full CFRP wrapping is used, a secondary separation in the CFRP fibers took place at the upper end. When this separation happens, the section became weaker leading to the formation of yield lines at this point which will lead to buckling after that.

SHS COLUMN WITH CFRP APPLICATION

The use of steel hollow tubular column strengthened with CFRP in existing structure is studied. Abraj Al-Kalaa Towers in Makka city adjacent to Holy Al-Haram Al-Makki are one of the biggest and highest reinforced concrete structures ever built (Fig. 13). After finishing building the six towers that surrounding the main middle tower of the clock (Makka clock) in Abraj Al Kalaa, the owners saw that pilgrims are using the roof to do their prayers. But the wind was very strong at roof level 286 m above the zero level of Al-Haram. So the designers (Architects) decided to add a steel structure on the roofs of the four towers so the roofs can be used for praying. The added steel structure was with dimensions controlled and forced by the architects to match the overall shape of the towers and not to add a bulky structure at top of these towers. This added structure was made of steel cold-formed sections of hollow square sections. The exterior columns of the added tent structure are inclined and under the action of suction forces and torsional loads due to the high wind at that level (286 m above the zero level of Al-Haram). The added structure is a tent made of a special fabric tissue fixed with steel hollow tubular columns. The exterior columns are inclined to resist the suction of the tent.

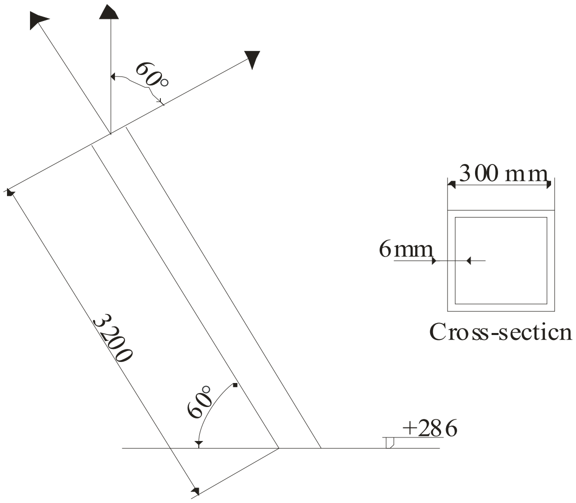
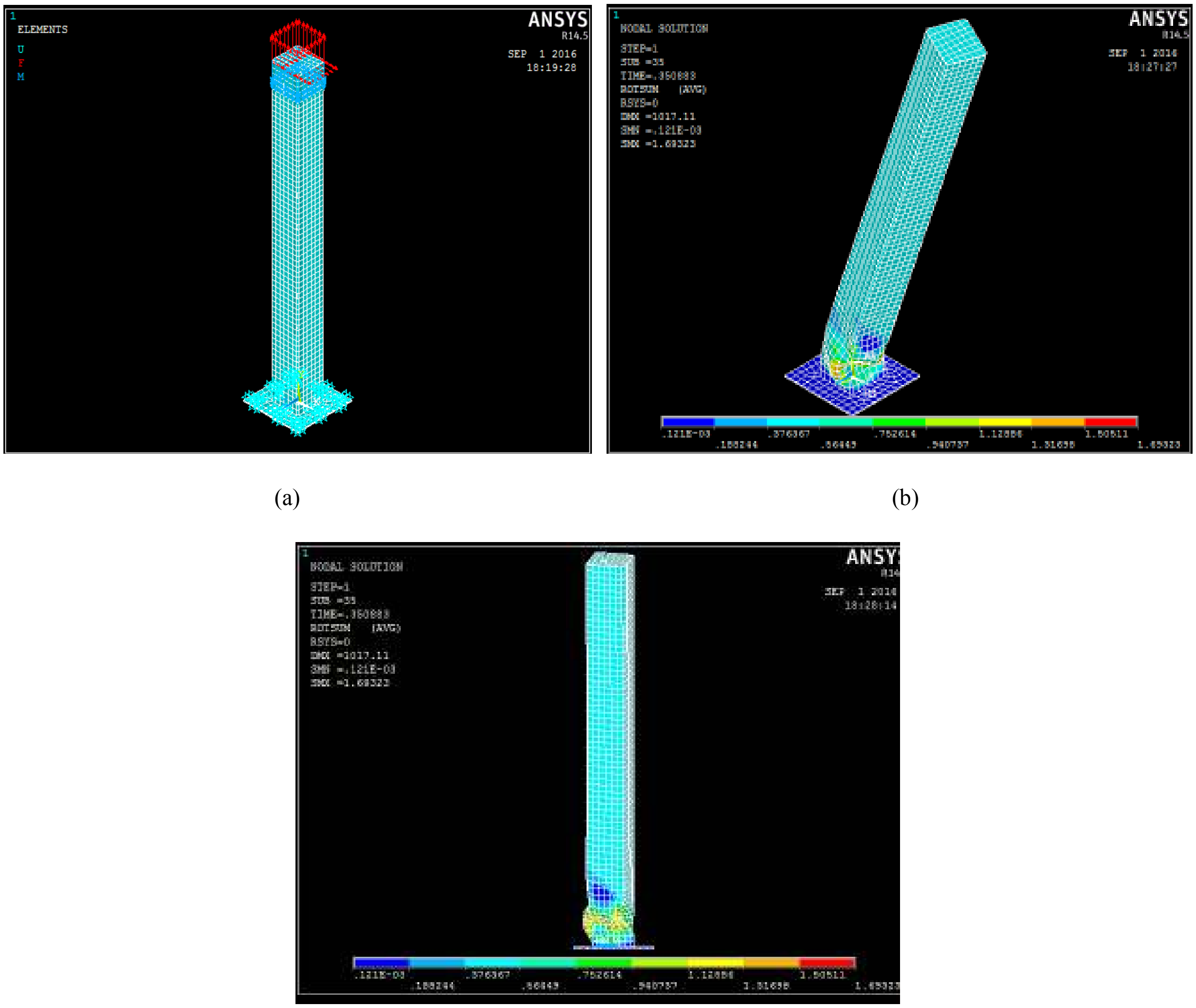


Fig. 14: Inclined column

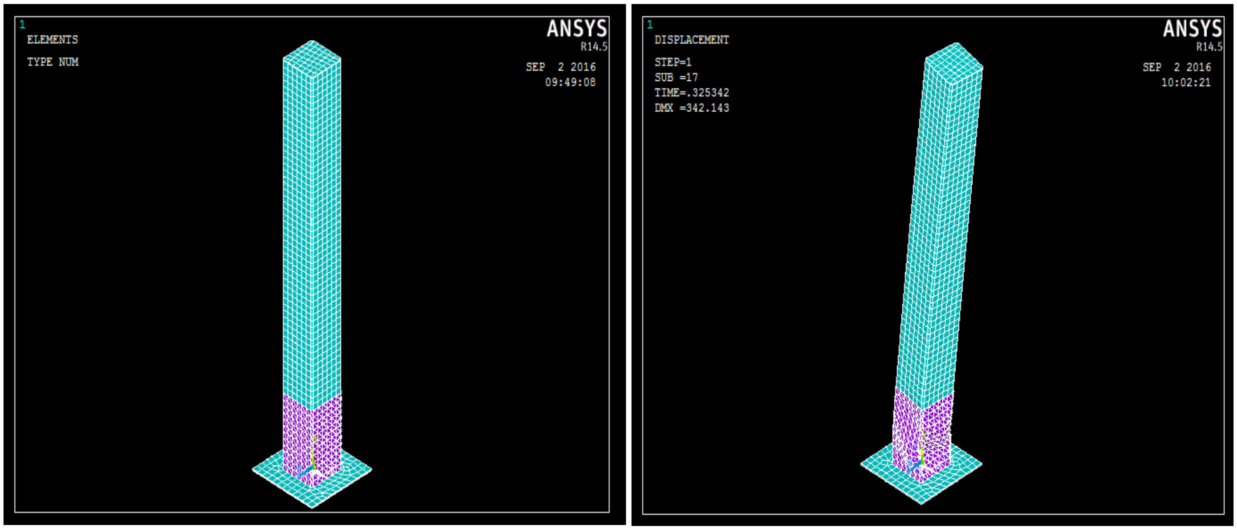
Inclined column with inclined force and torsion: It is an inclined column with angle of (60°) inclination and under the action of tensile force of (560 kN) tilted at an angle of (60°) towards the tent fabric as shown in Fig. 14. The forces acting at the wedges of the tent, has been analyzed into two perpendicular components. The high wind speed hitting the tent at that high level caused additional torsional forces besides the tensile force which yields a state of local buckling at the column base. To overcome this situation without increasing cross sectional dimensions, it was decided to add CFRP as an effective solution to increase resistance of the column to the loads and decrease the rotation angle at last stage tacking place at column base. In ANSYS program, the column is divided into (50×50) mm shell elements with a total number of (1956). The boundary conditions are applied on the base plate. 32-nodes spread over 8 places on the base plate are constrained in the X, Y and Z directions (UX = UY = UZ = 0) only. The load was applied at top of column gradually till its maximum value as shown in Fig. 15a. The rotation increased after the state of local buckling at base of column till the last stage of failure as shown in Fig. 15b and 15c. The work of strengthening includes the addition of four layers of CFRP wrapped with zero angle for length of 600 mm from the column base as shown in Fig. 16a. In ANSYS, SHELL41 is used to represent the CFRP layers. After completing the



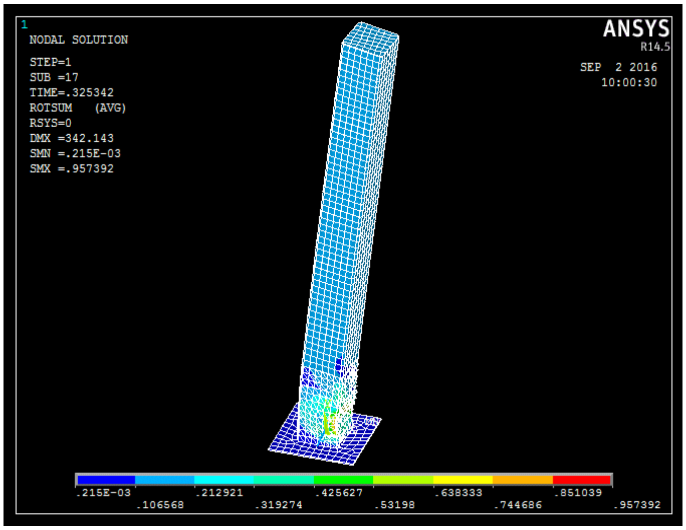
(a) (b)

(c)

Fig. 15: (a) Column meshing, boundary conditions and loading (b) and (c) Deformed shape at last stage



(a) (b)



(c)

Fig. 16: Configuration of CFRP for the column & deform shape after wrapping

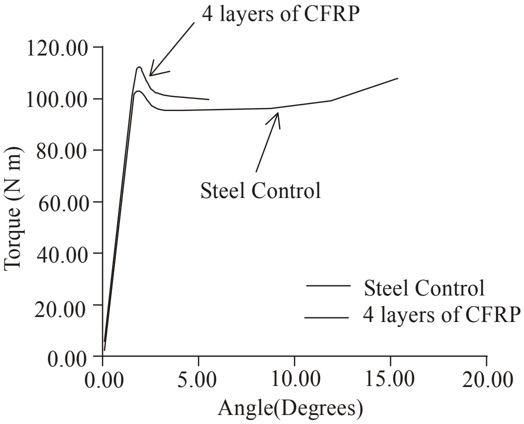


Fig. 17: Torque – Angle of twist curve for exterior inclined steel hollow tubular section with and without CFRP

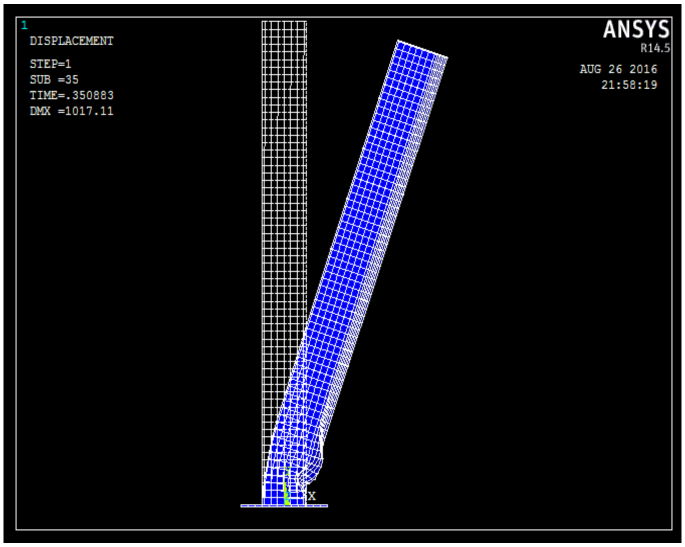


Fig. 18: Deformed shape at last stage without strengthening of CFRP

strengthening modeling, the load was applied at top of column gradually until its maximum value. The rotation increased after the start of local buckling took place at base of column till the last stage of failure as shown in Fig. 16b and 16c.

Figure 17 presents the numerical analysis output of torque-twist curve for the inclined column. This Figure shows a considerable increase in the maximum torsional capacity after strengthening, where the maximum torque was (103.47 kN.m) before strengthening and reached to (113.35 kN.m) after strengthening with percentage increase of (9.55%). Also, there is a clear decrease in the angle of twist of the model at last stage of failure, where the rotation angle reached before wrapping to (15.33°) and after the wrapping it became (5.5°) with a percentage decrease of (64%). This is the main reason behind using CFRP, where the designer wanted to decrease the torsional rotation took place on these columns and enhance its torsional capacity.

Figure 17 reveals the behavior of model before strengthening, where the curve begins trending up with the model approaching to failure stage where the peak load at this stage is (108 kN.m). The logical explanation for this situation is that the model has been subjected to two forces as well as the torque. The first force works in tension and the second force works to bend the column towards the X-axis. After the occurrence of local buckling, the column begins to bend towards the horizontal component reaching the center of the original force at angle (60°) as shown in Fig. 18. In this case, the column begins to act like a column under axial tension then the torque capacity increased whenever the column is closer to that angle.

CONCLUSION

- It can be seen from the numerical results of the finite element verification study that a considerable increase in maximum torsional capacity was gained for thin-walled square sections after strengthening with CFRP wrapping. This leads to strengthened sections can hold larger torsions without any appearance of local buckling in the range of original loadings.
- The amount of increase in the maximum torsional capacity is related to the wall thickness of the non-strengthened section. The larger section depth to wall thickness ratio (D/t ratio) the larger improvement in torsional capacity when compared to thicker wall tubular section having lower (D/t ratio).
- The behavior of thin-walled members is severely affected by the orientation and distribution of the CFRP laminates than the amount and number of CFRP layers.
- From comparison between the numerical (FEM) and experimental results of the verification study, the validity of the numerical analysis with the methodology developed gave maximum difference in the ultimate torque capacity of (10%) and the maximum difference in the ultimate rotation was (3%) for all tested specimens and analyzed members, which shows the reliability of the proposed numerical model.
- The use of four layers of CFRP wrapping for the inclined steel hollow columns of the roof tents of Jabal Al-Kalaa increased the torsional capacity of these columns and reduced the total angle of twist by (64%). It managed solving the buckling issue taking place at the bases of these columns effectively. This application encourages Architects to keep original sections suitable for the total form and shape of the building without changing them to larger sizes.

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