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Research Note

Numerical Study on Reinforcing of Thin Walled Cracked Metal Cylindrical Columns Using FRP Patch

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Abstract. *In this paper a new technique was proposed for the repair of defected metal columns. The finite element method was chosen to find out the adequacy of the proposed method, regarding, the load carrying capacity of two types of thin walled cylindrical columns with $L/D = 10$ and 20 along with circumferential and longitudinal cracks. The study considers the non linearity behavior in both material as well as geometrical characteristics. Various configurations of the composite patches made from carbon-epoxy were assumed on the cracked region and the influence of a patch on the load carrying capacity of the columns was examined. The obtained results indicate that composite material can not only compensate the effect of damage on column buckling load, but also increase buckling strength to a level even greater than in an intact one.*

Keywords: *Repair; Cracked metal column; Buckling load; FRP patch; Compression loading.*

INTRODUCTION

Nowadays, composite materials are utilized in various fields of industry and building construction due to their valuable properties such as the high value of strength to weight ratio and easy installation. From the prominent usage of these materials in civil engineering, it was addressed to the reinforcement and repair of concrete members [1]. Generally this application has been utilized more for concrete rather than metallic structures, while metallic structural members can be exposed to various damages and defects in their service lives, one of which being crack may stem from different factors such as sudden damage, corrosion environment or fatigue loading. Thus, demand for an efficient repair against these phenomena is a major concern of design engineers. On the other hand, using metallic patches and stiffeners requires heavy equipment. Even then welding of these structures, considering their small thicknesses, can be followed by temperature defects, extra residual stresses and unexpected deformation.

The presented technique was previously explored for repairing defected metallic structures, especially under tension loading rather than compression. As a literature review, Baker and Jones [2,3] studied a repair technique using adhesively bonded boron/epoxy composite patches, which is widely considered as a reliable method for repairing cracked plates under tensile loading. The authors of the present paper investigated the influence of patched FRP pultruded sheets on metal plates in the buckling phenomenon [4]. Teng and Hu [5] covered steel tubes and cylindrical shells under compression loading by FRP jackets during experimental and finite element studies and they displayed this technique as a useful method for ductility increase and collapse hindering of these structures. Silvestre et al. [6] investigated the non-linear behavior and load carrying capacity of the CFRP-strengthed open-section columns from cold-formed steel using pultruded composite sheets, and they observed a considerable increase in the buckling load and improvement of the post buckling behavior for these members. Shaat and Fam [7-9], using FRP sheets on hollow square columns, investigated the influence of these patches on the load-bearing capacity of the columns. They developed an

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analytical model for their experimental specimens and verified the analytical manipulation by experimental results. They also extended their theory for various characteristics of the columns, such as slenderness and initial out-of-straightness.

The main contribution of the current study is the stability of a repaired metal cylinder using an FRP patch. The influence of the crack in both longitudinal and circumferential directions was considered on the load carrying capacity of the cylinder. The methodology is based on numerical study. All the assumptions here are based on experimental observations by authors presented in other studies. The columns were made of steel alloy in those tests and here they are assumed from an aluminum alloy [10]. The obtained results would establish the presented retrofitting technique as a unique method for repairing and reinforcing thin walled tubular sections.

PROPOSED MODELS

To follow up the subject of the paper, the selected models are of two various diameters and of identical length and thickness as $L = 1000$ mm and $t = 1$ mm. The diameters were determined as $D = 50$ mm and $D = 100$ mm denoting the cylinder aspect ratio for exploring two distinct buckling mode shapes. The considered cracks on the columns were chosen in longitudinal and circumferential directions to investigate the influence of crack in two major orientations. The length of the longitudinal crack was assumed 0.2 of the column length ($C/L = 0.2$) and similarly the circumferential crack length was 0.2 of the column section perimeter ($C/2\pi r = 0.2$).

The column was made of an aluminum alloy (T-6061) with elastic modulus, yield stress and Poisson ratio equal to 71.7e3 MPa, 240 MPa and 0.33, respectively. It should be emphasized that due to the almost flattening out of stress strain in the plastic domain for the selected aluminum, T-6061, the material behaves in an elastic-fully plastic manner. By placing two rigid plates at both ends, the end conditions of the columns were considered as clamped. The criterion of the cylinder shortening provided movement between the two rigid plates. The reinforced material was chosen as carbon fiber and epoxy resin with mechanical properties as listed in Table 1. In this table, E_1 is the module of the composite in the fibers direction, E_2 is the composite module in the matrix direction, ν_{12} is the major Poisson ratio in the 1-2 plane, G_{12} is the major shear module in the 1-2 plane, X^T denotes the tensile strength in the fibers direction, X^C indicates the compressive strength in the fibers direction, Y^T denotes the tensile strength in the matrix direction, Y^C represents the compressive strength in the matrix direction and, finally, S_L and S_T denote the shear strength in the fibers and matrix directions, respectively.

Figure 1 shows the schematic view of the repaired cylinder. Here, the important problem is the interaction between the cylinder and the FRP patch. To determine this relation regarding that observed in the experimental study about contact between the FRP patch and cylinder in [10], in the present study, any debonding between the patch and cylinder was ignored and the movement of the patch elements depended on the movement of adjacent cylinder elements. The assumption was validated in the experimental observations carried out by the authors in previous work [5]. Of course, the mentioned hypothesis ignores any debonding between a composite patch and a metal cylinder.

FE MODELING

Cracked Cylinder

The common commercial program, ABAQUS [11], was utilized for the FE modeling and analysis of the assumed columns. For modeling of the columns, nonlinear behavior in both material and geometry

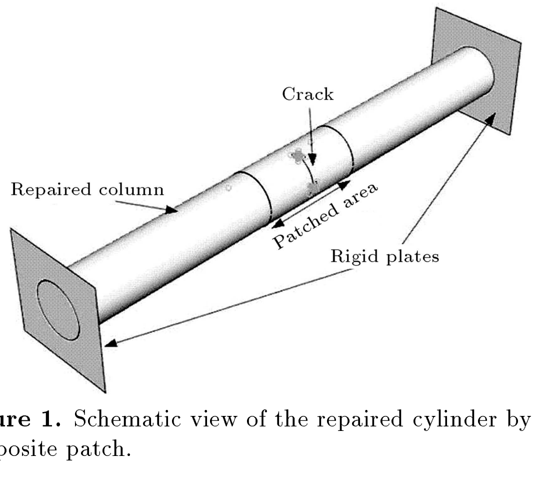

Figure 1. Schematic view of the repaired cylinder by composite patch.

Table 1. Mechanical properties of the used FRP.

Material	E_1 (MPa)	E_2 (MPa)	ν_{12} (MPa)	G_{12} (MPa)	X^T (MPa)	X^C (MPa)	Y^T (MPa)	Y^C (MPa)	S^L (MPa)	S^T (MPa)	t (mm per layer)
Carbon/epoxy	140421	8982	0.3	3387	800	1100	150	231	520	280	0.2

domains was considered for the models. Loading on the structures was carried out considering a low velocity ($V = 5$ mm/s) on the top rigid plate. In order to consider the nonlinearity in geometry, at the beginning, the buckling analysis was performed and then by imposing the combination of obtained mode shapes, considering them as an initial imperfection, the non linear analysis was conducted. The amplitude of the small deformations was considered about 1 μm. The assumed boundary conditions, both for the top and bottom plates, were implemented as three rotational and two translational movements. The contact between the rigid plates and the cylinder edges was defined both in normal and tangential directions. The normal contact was designated as "hard contact" and the tangential contact was introduced with a friction ratio to prevent sliding between the plate and cylinder. The presented results are the axial load-end shortening curves, which were compared for the intact, cracked and repaired columns. Both cylinders and rigid plates were modeled using "shell" elements, and for this purpose, "S4R" element with 4 nodes and 6 degrees of freedom (three translational and three rotational) per node was chosen from the element library of the "ABAQUS.CAE". A mesh convergence study for an intact cylinder with $L/D = 10$ was carried out to choose the appropriate size for mesh dimensions (see Table 2). The buckling process is explained as follows: The plastic buckling takes place at two ends and the diameter of the cylinder increases in this region. Considering the yield stress, σ_y, equal to 240 MPa, the yield load, P_y, is then estimated as = 75.4 KN, which is similar to numerical FEM results. Thus, starting with a 30*30 mm^2 finite element mesh, using non-linear analysis, a convergence study was conducted for an intact cylinder with $L/D = 10$. The result from each refinement of the mesh is compared with that of the classical buckling equation (P_y) and is summarized in Table 2. Accepting an error margin of 1% for the non-linear buckling load, a mesh consisting of 4000 elements and 10 mm*10 mm element size was adopted in the numerical analyses. Regarding the dependence of the accuracy of the results on the ratio between mesh size and cylinder radius, the size of mesh for a cylinder with $L/D = 20$ was chosen as half of a cylinder with $L/D = 10$. This size of mesh was extended for the entire structure except at the vicinity of the crack tips. Observation of the stresses around the crack tip shows that the mesh size in this region has a dominant effect on the stress contour in the region. It was decided to fragment the mesh size at this region to about 1/16 the size of mesh in other regions through four steps [12]. Triangular elements were chosen for meshing of the regions near the crack tips in order to prevent making narrow rectangular elements in these areas.

Table 2. Mesh convergence study of the cylinder with $L/D = 10$.

Mesh Size (mm)	Number of Elements	Buckling Load (KN)	Error (%)
30*30	428	77.578	2.90%
20*20	1000	77.059	2.20%
15*15	1745	76.682	1.70%
10*10	4000	76.169	1.02%
7.5*7.5	6951	76.116	0.95%
5*5	15600	76	0.80%

Composite Patch

For modeling of FRP patch confinement, various methods have been implemented by researchers. In the current study, the composite patch was modeled using shell elements. The centroid of the patch elements was located at an appropriate distance from the centroid of the metal cylinder. An offset was assigned to all contributed nodes for contact between cylinder and patch nodes. The continuity between the patch and cylinder during the loading process was fully established and the deformation of these two parts was assumed identical. Using "tie" constraint as the direct contact between patch and cylinder nodes, the full bonding will, then, be provided. By defining this constraint, the degrees of freedom of the patch elements were introduced as slave elements and those of the cylinders as master elements with consideration of no debonding between the patch and cylinder. "S4R" shell elements were adopted to model the laminated composite patch with orthotropic characteristics and a progressive damage capability. For all proposed models, the fibers were oriented in a circumferential direction in the retrofitting of both crack types: longitudinally and circumferentially.

Progressive Damage

The elastic damage modeling was investigated in the same way as damage initiation and progression in brittle anisotropic materials such as FRP. In this theory, the damage is modeled by reducing the stiffness of materials, based on Hashin and Rotem criteria (1973) [15,16]. In the present modeling, four various modes are considered for damage of the composite:

- Fiber rupture in tension.
- Fiber buckling and kinking in compression.
- Matrix cracking under transverse tension and shearing.
- Matrix crushing under transverse compression and shearing.

On the basis of the four mentioned modes, four damage criteria are introduced to initiate the damage as follows:

- $F_f^t = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$

- $F_f^C = \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2.$

- $F_m^t = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$

- $F_m^C = \left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\hat{\sigma}_{22}}{Y^C} + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$

In the above equations, $\hat{\sigma}_{11}$, $\hat{\sigma}_{22}$, $\hat{\tau}_{12}$ are components of the effective stress tensors which are intended to represent the stresses acting over the damaged area. α is a coefficient that determines the contribution of the shear stress to the fiber tensile initiation criterion and which varies between 0 and 1, its high value being assumed here. At the end of each state of analysis, these criteria were checked on each element of the FRP, whether the damage was initiated or not. Having damage evolution definition for each mode, the stiffness of the damaged element is replaced by zero in that mode. For a metal cylinder, the Von-Mises stress criterion was used and for FRP elements, the Hashin damage criterion was evaluated. These are shown with: HSNFTCRT for maximum value of the fiber tensile initiation criterion experienced during the analysis or ultimate F_f^T; HSNFCCRT for maximum value of the fiber compressive initiation criterion experienced during the analysis or ultimate F_f^C; HSNMTCRT for maximum value of the matrix tensile initiation criterion experienced during the analysis or ultimate F_m^T, and HSNMCCRT for maximum value of the matrix compressive initiation criterion experienced during the analysis or ultimate F_m^C.

DISCUSSION OF THE RESULTS

Repair of Circumferentially Cracked Column with $L/D = 10$

A relatively long cylinder was included in this study in order to investigate the efficiency of the proposed technique to repair cylinders which have plastic buckling. The load versus axial shortening in a non-linear manner is depicted in Figure 2, in a non-dimensional graph where the vertical axis is the ratio of the applied load (P) to the ultimate strength (P_0) of the intact cylinder and the horizontal axis gives the ratio of the end shortening (Δ) over the cylinder length (L). According to the figure, in the presence of a circumferential crack with $C/2\pi r = 0.2$, the ultimate strength and

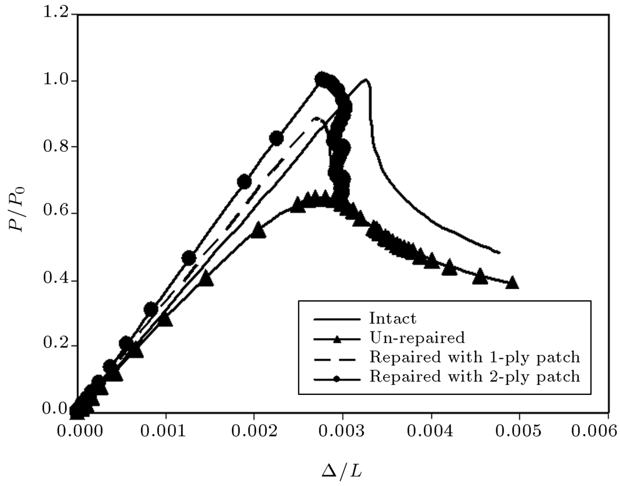

Figure 2. The influence of repair with composite patch on the non-dimensional load-deflection graph of the circumferentially cracked column with $L/D = 10$ and $C/2\pi r = 0.2$.

absorbed energy of the cylinder were decreased by 37% and 27%, respectively; "C" denotes the length of the crack. Figure 3 shows the buckling deformations of the cylinders in states of being intact and cracked. It is seen that the buckling of the column deforms from the elephant foot mode of an intact cylinder to the local crippling mode at the cracked region for a cracked cylinder. In the first attempt, only a one-ply composite patch made of carbon-epoxy with fiber orientation in the circumferential direction and with a length of "200 mm" was used on the cylinder axisymmetrically relative to the crack. The maximum buckling load was considerably promoted, as can be seen in Figure 2. The next attempt was specified by strengthening of the cracked region using a two-ply composite patch. Figure 2 also shows its influence on the load bearing behavior of the repaired column. Figure 3d shows the buckling deformation of this cylinder, which was occurred out of the patch zone. Figure 4 shows the Hashin damage criterion about the tensile fibers for both types of composite patch.

Repair of Longitudinally Cracked Column with $L/D = 10$

In order to investigate the influence of the longitudinal crack on this column, the size of crack was assumed about 0.2 of the column length at the center. Figure 5 shows the non dimensional load deflection curves of longitudinally cracked cylinders. The repairing patch has enhanced the cracked cylinder buckling load up to the intact one. The buckling form of the cylinder is observed in Figure 6 in the presence of a longitudinal crack. The cylinder inclines outward from the cracked region followed by its collapse. To repair this cylinder, a two-ply patch with a length of "300 mm" was

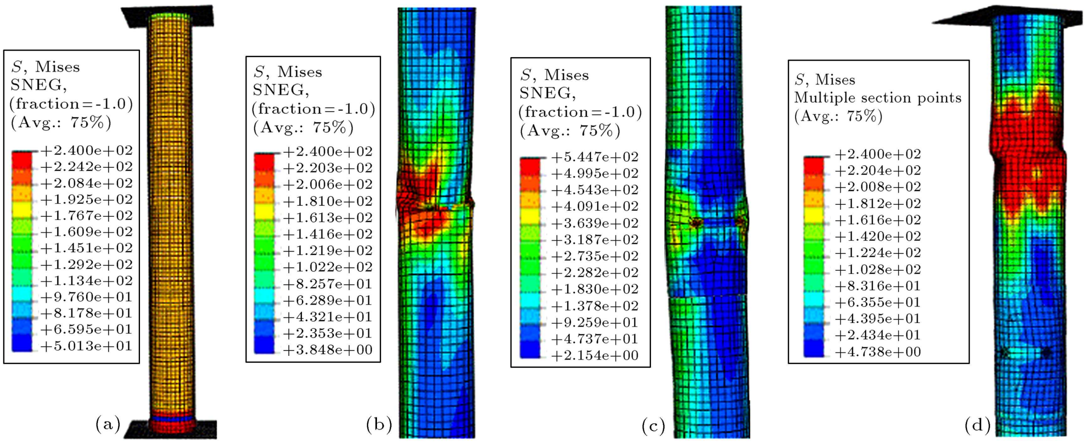

Figure 3. Buckling deformations of the column with $L/D = 10$ in states of (a) intact; (b) un-repaired circumferentially cracked; (c) patched by 1-ply patch; and (d) patched by 2-ply patch.

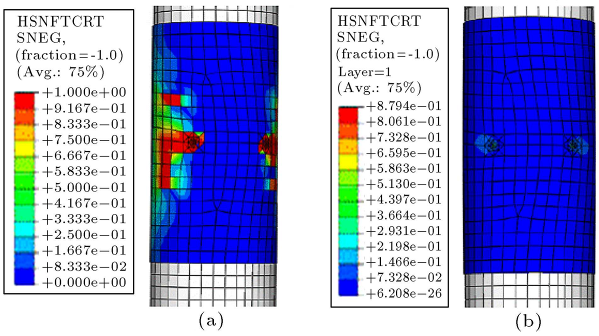

Figure 4. Hashin damage criterion about the tensile fibers in (a) 1-ply patch and (b) 2-ply patch.

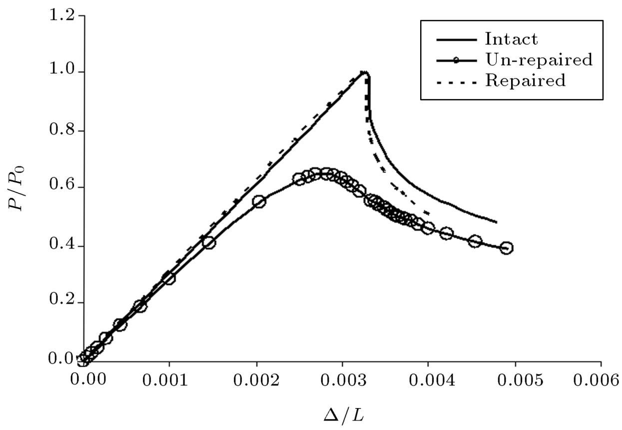

Figure 5. The influence of repair with composite patch on the non-dimensional load-deflection graph of the longitudinally cracked column with $L/D = 10$ and $C/L = 0.2$.

attached on the crack axisymmetrically relative to the crack centre. In Figure 6b, the buckling form of the retrofitted column appeared in an elephant foot mode at one end of the cylinder. Based on the obtained results, none of the damage criteria was referred to FRP failure, which indicates the successful performance of an externally bonded composite patch on longitudinally cracked circular columns.

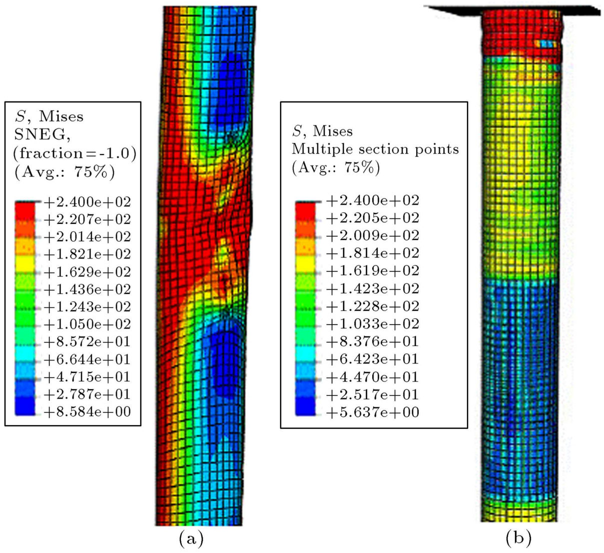

Figure 6. Buckling deformations of the longitudinally cracked cylinder with $L/D = 10$ in states of (a) un-repaired longitudinally cracked and (b) repaired by composite patch.

Repair of Circumferentially Cracked Cylinder with $L/D = 20$

This section was studied in order to investigate the applicability of the proposed technique for long columns pronouncing Eulerian type buckling mode. The buckling form of the intact column is observed in a fully elastic domain, which is depicted in Figure 7. Similar to the previous model, the assumed circumferential crack size for this case is 0.2 of the perimeter of the cylinder. Inserting the circumferential crack decreased

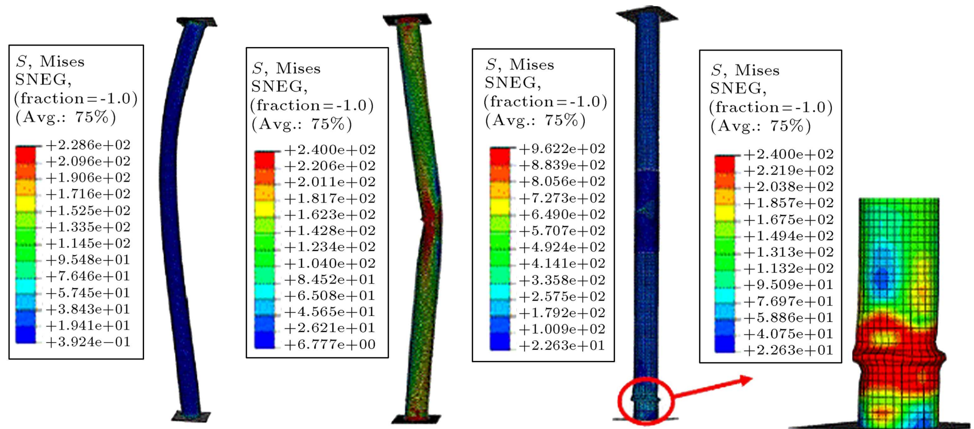

Figure 7. Buckling deformations of the cylinder with $L/D = 20$ in states of (a) intact; (b) un-repaired circumferentially cracked; and (c) repaired by composite patch.

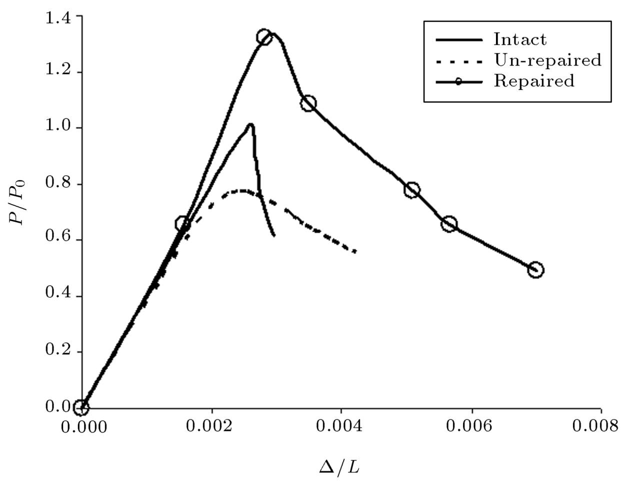

Figure 8. The influence of repair with composite patch on the non dimensional load-deflection graph of the circumferentially cracked column with $L/D = 20$ and $C/2\pi r = 0.2$.

the column ultimate strength about 23% (see Figure 8). According to Figure 7, the buckling shape is outward deformation form cracked region. In order to repair of this cylinder a two-ply patch with a length of "200 mm" was used on the cracked surface and the buckling strength enhanced about 35% in comparison with the intact column (see Figure 8). According to this figure, the obvious reason for enhancement of the load bearing capacity of the reinforced column is transformation of the buckling phenomenon from the Eulerian mode to the local plastic buckling mode, which was occurred in the un-patched zone. The main reason for these phenomena is the interaction of the patch on the length of the cylinder. In fact, the patch divides the cylinder into shorter lengths: patched length and un-patched length. So, the local mode would then be governed to the plastic buckling by an un-retrofitted area that improves the buckling behavior of the column to a possibly more favorable mode than the other with higher strength and more ductility.

Repair of Longitudinally Cracked Cylinder with $L/D = 20$

Applying the same size of crack in a longitudinal direction equal to 0.2 of the cylinder length located at the mid length of the cylinder the buckling strength of this defected column was reduced to about 20% of the intact one with the buckling mode shape at an outward inclination from the cracked region. The variation of non dimensional applied load versus axial shortening is depicted in Figure 9. The considerable increase in buckling strength of the retrofitted column with a two-ply patch and length of "200 mm" is observable. The fibers orientation was assumed in a circumferential

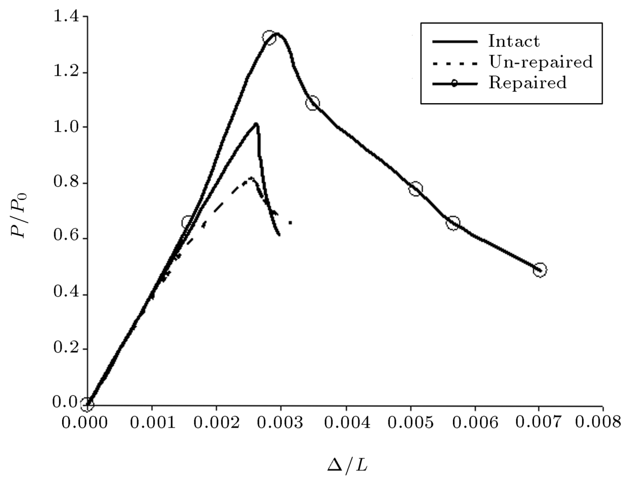

Figure 9. The influence of repair with composite patch on the non dimensional load-deflection graph of the longitudinally cracked column with $L/D = 20$ and $C/L = 0.2$.

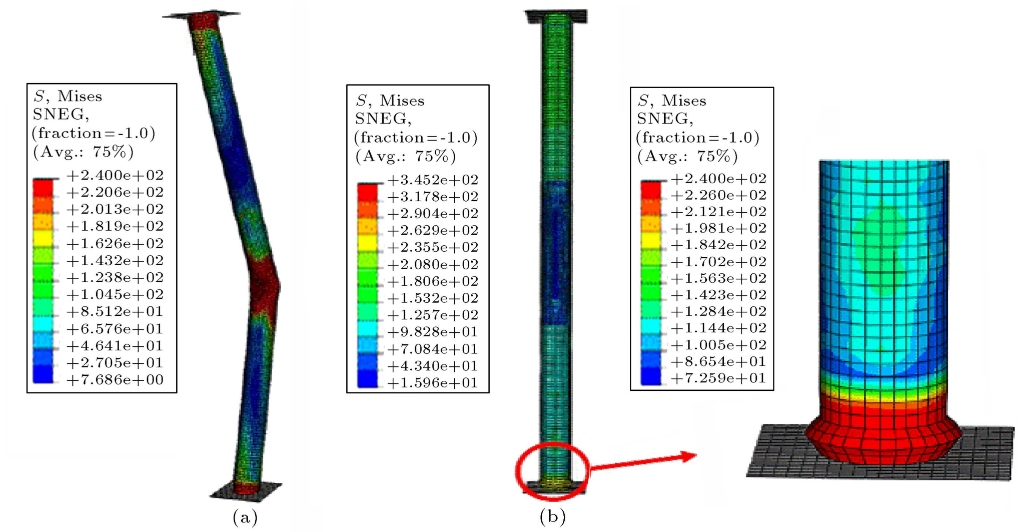

Figure 10. Buckling deformations of the longitudinally cracked cylinder with $L/D = 20$ in states of (a) cracked un-repaired and (b) repaired by composite patch.

direction. Figures 10a and 10b show the buckling deformation of the cracked un-patched and patched columns, respectively. The damage indices show values far from failure, which indicate the high success of the proposed repair scheme for this case as well.

CONCLUSIONS

In the present paper, FRP wrapping of the defected metal columns was proposed as an effective technique for repairing of these members. In this regard, two sizes of column length: $L/D = 10$ and 20, were studied to investigate the adequacy of the proposed technique for two prominent buckling shapes. For this purpose with the assistance of a FE program, the influences of FRP local patches for on the repair of circumferential and longitudinal cracks were studied on the load carrying capacity of columns. The following results can be marked as useful conclusions:

1. The circumferential crack on the relatively long column with $L/D = 10$ reduced the ultimate strength about 37% and, by using a partial patch on the cracked region, the ultimate strength of the cracked column was fully recovered.
2. The longitudinal crack on the column with $L/D = 10$ reduced the ultimate strength by 35%; the application of the composite patch could return its load carrying capacity to that of the intact one, and the buckling failure was moved to the un-patched region.
3. The circumferential crack on the column with $L/D = 20$ reduced the ultimate strength by 22%, however, implementing the composite patch not only recovered the load carrying capacity but also could enhance the ultimate strength of the reinforced column by 35%, in comparison with the intact column.
4. The longitudinal crack on the cylinder with $L/D = 20$ reduced the ultimate strength by 20%. By applying the FRP patch, the buckling strength surpassed the intact column strength and, also the buckling mode would then transform from elastic Eulerian to local plastic mode.
5. The obtained results in this paper not only introduced the proposed technique as an efficient repair method for defected cylinders, but also showed its capability to improve the load bearing behavior of the columns in comparison with intact ones. Therefore, the FRP wrapping technique can be applied as a very unique and promising method for the repair, retrofit and reinforcement of metal columns.

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