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PERFORMANCE OF DEFICIENT STEEL HOLLOW SQUARE SECTION SHORT COLUMN STRENGTHENED WITH CFRP

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ABSTRACT

Strengthening with bonded CFRP-laminates might be an effective repair method to restore the load-carrying capacity of deteriorated steel elements. So, a deficient column needs to treat due to reducing in strength capacity as a damage of column because of extra loading or presence of dynamic loading. In this paper, short hollow square column made from hot rolled steel was analyzed under static loading to check out the column capacity and then same column with deficient as surface area ratio in different layout were studies under the effects of static and dynamic loading. The main parameters are number of layer as thickness amount of Carbon Fiber Reinforced Polymer, surface area ratio of deficient and deficient layout. Finite elements method as numerical solution by ANSYS software was adopted to simulate all models and presented as three dimensional problems. The analysis indicated that the deficient locations and sizes play important parameters in column strength and serviceability. And the harmonic load results must considered because of giving different performance from that under static loading by enhancing performance of strengthened columns and the presence of CFRP decreased the displacement in case of deficient column.

Keywords: short steel column, deficient, CFRP strengthening, finite elements, ANSYS, dynamic loading.

INTRODUCTION

Bonding composite materials to strengthen structural elements has attracted a great deal of attention during the last years. The use of Carbon Fiber Reinforced Polymer (CFRP) externally to reinforce many structural elements such as steel, concrete or composite section for the purposes of strengthening or recovering the strength lost in the deficient members. In structural steel columns, the CFRP adopted to treat the elements that damaged in such a way to re-strength the steel columns. The mechanical properties as tensile strength and other properties such as light weight, high corrosion resistance and be easy to the process of putting a decision or plan into effect make these material better than others or another solutions for strengthening method of structural elements. In 2016, Mohammad Reza *et al,* [1], studied the behavior of square hollow section in case of presence of initial horizontal or vertical deficiencies that strengthened by CFRP under the effect of static loading. The experimental and numerical results indicated that the presence of CFRP recover the strength due to the existence of deficient. In 2008, Guo Z.X. *et al*, [2], investigated the deficient reinforced concrete columns under the effect of seismic loading. The geometry of columns that adopted was square and half scale. The retrofitted method was steel jacket which showed an effective solution due to test results. In 2013, Iftekharul Alam*et al,* [3], focused into the steel column capacity strengthened by CFRP under impact loading by finite elements method. The analysis results be obviated the enhancement of strengthened of steel column in presence of CFRP as compared with the control model without CFRP. In 2016, Masoomeh Karimian*et al*, [4], looked out on the strengthening of short damaged steel columns by CFRP. A finite element approached by ABSQUS software was adapted to analyze the short circular steel columns. Analysis results showed that the presence of deficient reduced the strength capacity of the steel columns and the using of CFRP recover this strength. In 2009, Saptarshi Sasmal [5], investigated and evaluated the deficient that occurs in structural elements and the connections between them under the effects of cyclic loading. Numerical analysis by ATENA software was taken and the results are compared with the test specimen's results and showed good agreements. In 2015, Ghaemdoust *et al,* [6], explored the strengthening of deficient box steel column by CFRP. Finite elements method was adopted by ABAQUS software and the analysis results indicated that the use of CFRP make the steel column stronger in strength axial capacity.

In present manuscript, performance of initially deficient square steel column strengthened by CFRP under static and dynamic loading are studied. And it focuses on the finite element (FE) numerical modeling and simulation of CFRP strengthened steel column to predict its behavior and failure modes. The parameters that adopted in present paper are loading type, CFRP layers and the deficient layout and location.

LIMITS AND METHODOLOGY

Analysis and design of hollow square section column (HSS) by adopted the AISC - 360 - 16 [7], that classified as compact, non-compact, slender webs or flanges. Many factor that effect on the column stability such as flexural, axial, second order analysis and inelasticity. The Load Resistance Factor Design (LRFD) was adopted in design of steel column as a compact section so that the required width to thickness ratio for a member subjected to axial compression:

$$b/t < 1.4\sqrt{\frac{E}{F_y}} \tag{1}$$

Where, b is the width of hollow structural sections (HSS), t is the wall thickness, E is the modulus of elasticity and F_y is the yielding strength.

Based on the requirements and recommendations of AISC- 360 - 16 [8], the nominal wall thickness according to ASTM A1065/A1065M [8] or ASTM A1085/A1085M [9] that t equal to (0.93) the nominal thickness. The design compression capacity $\phi_c P_n$ of the (HSS) is:

$$P_n = F_{cr} A_g \tag{2}$$

$$F_{cr} = (0.658^{\frac{F_y}{F_e}}) F_y \tag{3}$$

$$F_e = \frac{\pi^2 E}{(\frac{L}{r})^2} \tag{4}$$

Where, F_{cr} is the critical stress, A_g is the gross cross-sectional area of member, E is the modulus of elasticity of steel, F_e is the elastic buckling stress, F_y is the minimum yield stress, r is the radius of gyration and ϕ_c equal to (0.90). The mechanical properties and the geometrical dimensions of HSS is listed in Table-1 and the mechanical properties for CFRP in Table-2 [1].

Table-1. Mechanical properties and dimensions of steel column.

Width (mm)	**Height** (mm)	**Long** (mm)	**Wall thickness**(mm)	**Yield tensile strength** (MPa)	**Modulus of elasticity** (MPa)
90	90	270	3	190	200000

Table-2. Mechanical properties of CFRP.

Thickness (mm)	**Tensile strength** (MPa)	**Modulus of elasticity** (MPa)
0.131	4300	238000

Deficient layout

Different layouts of deficient represent as size, location and direction as surface area ratio. Table-3 lists the deficient ratio and size. The columns height is same for all (270 mm) with geometry (90x90x3 mm), where the thickness is (3 mm).

Table-3. Deficient ratio and size.

Case	**Deficiency ratio**			**Location**
	Ratio	**L** (mm)	**W** (mm)	
1	0	0	0	-
2	0.05	60	20	Front middle
3	0.15	180	20	Front middle
4	0.05	60	20	Corner
5	0.15	180	20	Corner
6	0.05	60	20	One - third Middle up
7	0.05	60	20	One - third Middle base

Static and harmonic loadings

The applied static loading based on the calculations by used equations mentioned above and by the experimental capacity [2]. In case of frequency-domain analysis is based upon the dynamical response of the structure to harmonically varying load [10]. The external applied forces are sine and cosine functions, so that for each frequency, the loading varies with time [10]. The solution of applied external loading is the steady-state analysis that computes the deterministic response of the column at each specific frequency. The applied loading has components which acting at different phase angles, so that the harmonic loading is of the form:

$$P(t) = P_x \cos(\omega t) + P_y \sin(\omega t) \tag{5}$$

$$Mu''(t) + Cu'(t) + Ku(t) = P_x \cos(\omega t) + P_y \sin(\omega t) \tag{6}$$

Where (ω) is the circular frequency of the excitation, P_x and P_y are the components of applied loading in the horizontal and normal directions, t is the time. The equilibrium equation for the structural system is Equation (6):

Where (K)is the stiffness matrix, (C) is the viscous damping matrix, (M)is the diagonal mass matrix, and (u''), (u'), and (u) are the node accelerations velocities, and displacements, respectively. The applied frequency range classified as low that ranged (0-40 Hz) and medium (40-400 Hz) adopt in present study.

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Numerical modeling

All models are simulating using finite elements approach by ANSYS version 16.20. SOLID185 [10] is used to simulating the steel columns because of a three dimensional of solid structures that defined by (8) nodes with three degrees of freedom at each node as shown in Figure-1. SHELL41 for CFRP that a three dimensional element having membrane stiffness without bending stiffness with three degrees of freedom at each node as shown in Figure-2. The numbers of meshes are selected to match the convergence requirements and the size of deficient so that the convergence criteria as displacement with (3%) of tolerance. The Newton -Raphson numerical roots method is adopted to determine the unknown and Frontal solver for dynamic analysis with proper material models, suitable boundary condition simulation, convergence criteria and solution method.

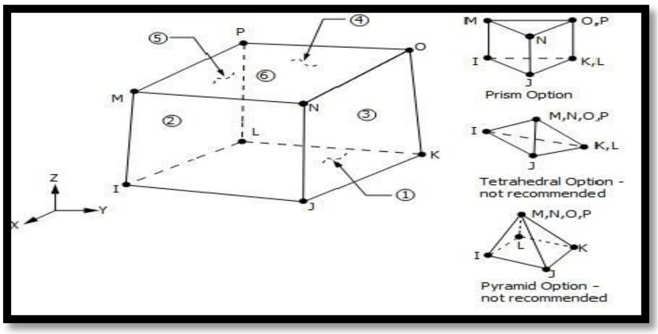

Figure-1. SOLID185 element [10].

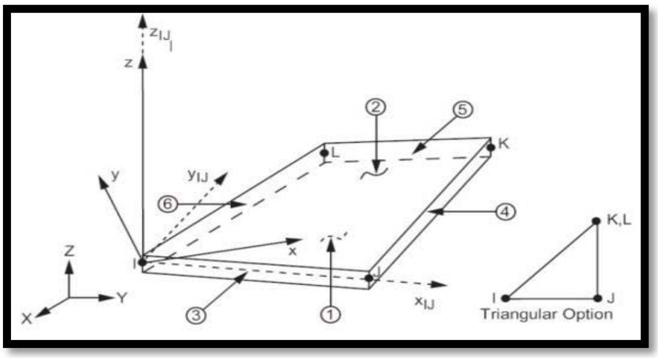

Figure-2. SHELL41 element [10].

RESULTS

Figure-3 represents the mesh of the steel columns that all models are the same in mesh sizes but different in deficient size and location which shown in Figures 4 to 9. Figures 10 to 30 show that the axial, lateral displacements and axial stress for all cases under applied static loadings. The Figures 31 to 33 represents the comparisons between all cases as axial, lateral displacements and axial stress at the point of maximum axial displacement up to the ultimate static loadings. The Figures 34 to 36 represents the comparisons between all cases as axial, lateral displacements and axial stress at the point of maximum axial displacement up to the ultimate harmonic loadings. The Figures37 to 39 represents the comparisons between all cases as axial, lateral displacements and axial stress at the point of maximum axial displacement up to the ultimate static loadings in cases of columns with CFRP. The Figures 40 to 42 represents the comparisons between all cases as axial, lateral displacements and axial stress at the point of maximum axial displacement up to the ultimate harmonic loadings with and without of CFRP. The maximum axial displacements for all models are summarized in Table-4 with corresponding maximum load.

Table-4. Maximum axial displacements under the effects of static and harmonic loadings.

Model mark	**Maximum load** (kN)	**Maximum axial displacement - static loading** (mm)	**Maximum axial displacement- harmonic loading** (mm)	**Frequency** (Hz)
Case 1	249	1.576	1.567	1400
Case 2	161	5.051	1.371	700
Case 3	167	0.966	0.325	900
Case 4	160	1.005	3.600	1300
Case 5	169	0.929	1.551	800
Case 6	160	1.407	3.588	1400
Case 7	160	0.868	1.376	800

The axial displacements increase as the location of deficient near corner and the ends (boundaries) of the column. The lateral displacement that represent the buckling of the column is small and become very small and near to zero in case of presence of CFRP around the column at distance equal to the width of deficient at the top and bottom of deficient because of the CFRP gave confinements and work like ties in reinforced concrete column so that they prevent buckling specially at center of column. Also, the axial displacement increase at the top of

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the deficient and the axial stress concentration around deficient. Figure-31 shows that the maximum axial displacement occurs in case of central deficient and in Figure-32 the maximum buckling occurs in case of 1 and 5 while the maximum axial stress occurs in case of 1. The harmonic loading applied in same amount as static loading but dynamically and all analysis results were at the point of maximum axial displacement for each column. The maximum axial displacements in case of dynamic loading greater than that in static loading except that in case 2 and 3. When the displacements under the effect of harmonic loading is more that for static loading that mean it must be considered and redesign of the column taking into account the dynamic load analysis. The frequencies which cause displacements and stresses concentration does not cause resonance that make sudden failure of the column. In this study, all frequency range did not cause resonance but gave higher axial stresses. In presence of CFRP the axial displacement reduced to (1.04 mm) and (1.09 mm) by using of two and one layer around the deficient in case 2 that is less than the displacement in control column. The lateral displacement becomes close to zero in presence of CFRP because of the confinements surrounding the column. The design strength capacity of column; axial and lateral displacement and axial stress are checked first in model case 1 under static loading based on AISC-360-16 and evaluated with the principle of axial displacement and axial stress of strength of material and also the strength by equations 1 to 4 mentioned above. The displacement of control column at applied failure load obtained by [1] is greater than the serviceability of the column. In case of static loading, Table-4 the static vertical displacement in case of failure load for all columns are greater than the displacement that calculated by using the fundamental of strength of material because of in model the applied loadings are failure load.

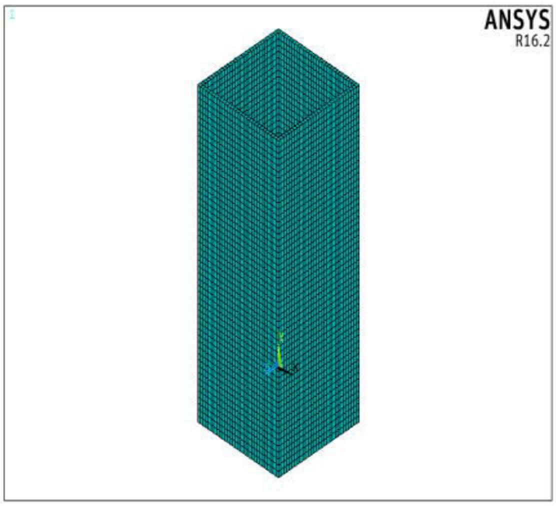

Figure-3. Mesh elements of steel column - case 1.

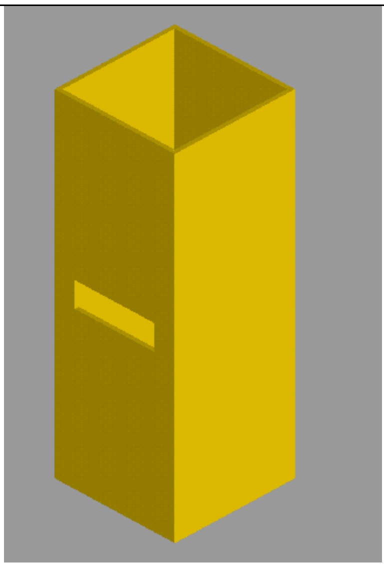

Figure-4. Case 2.

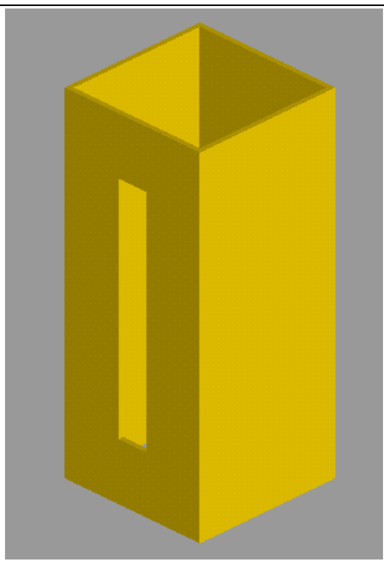

Figure-5. Case 3.

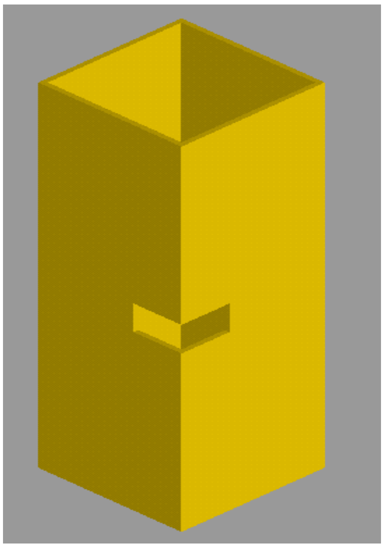

Figure-6. Case 4.

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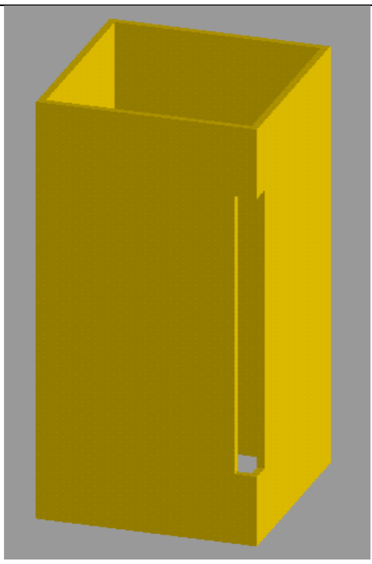

Figure-7. Case 5.

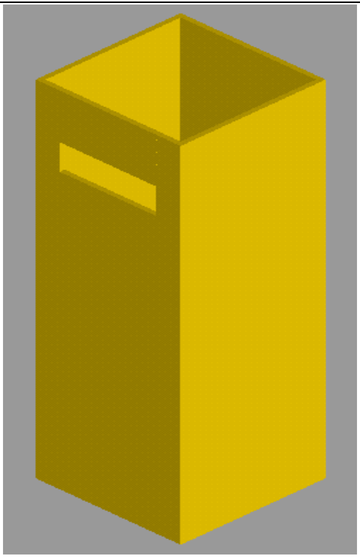

Figure-8. Case 6.

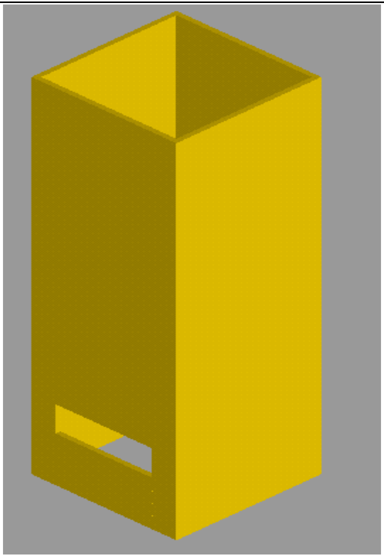

Figure-9. Case 7.

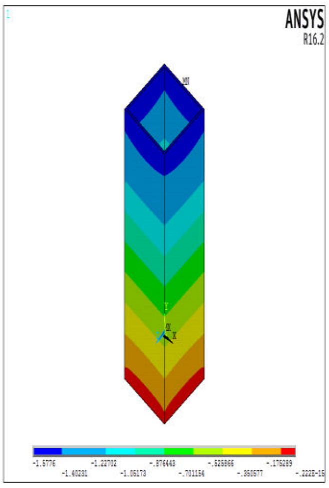

Figure-10. Axial displacement - case 1.

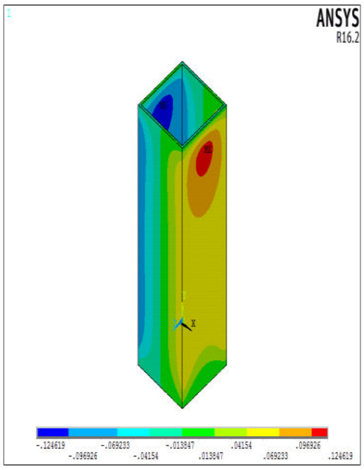

Figure-11. Lateral displacement - case 1.

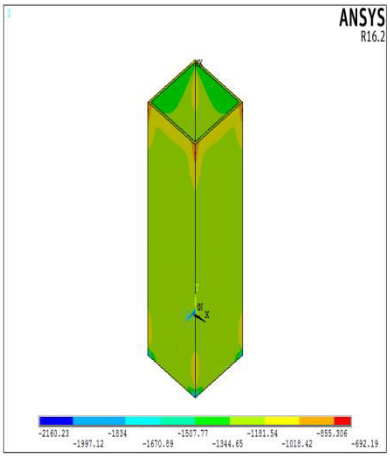

Figure-12. Axial stress - case 1.

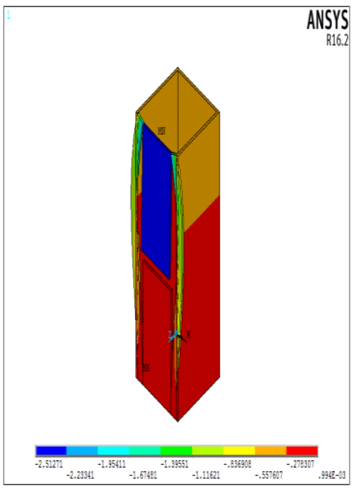

Figure-13. Axial displacement- case 2.

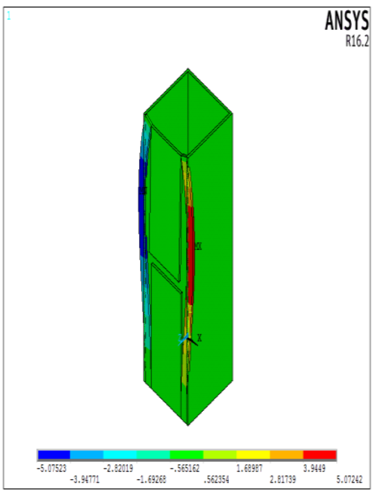

Figure-14. Lateral displacement- case 2.

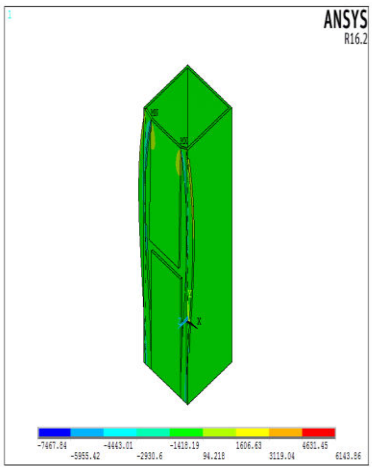

Figure-15. Axial stress - case 2.

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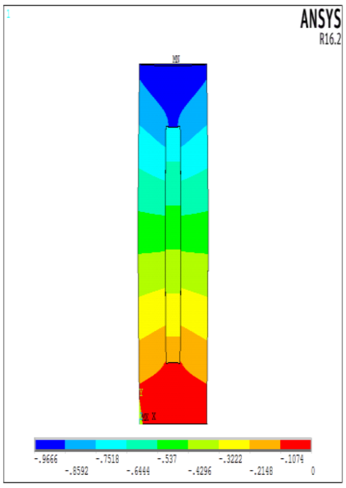

Figure-16. Axial displacement-case 3.

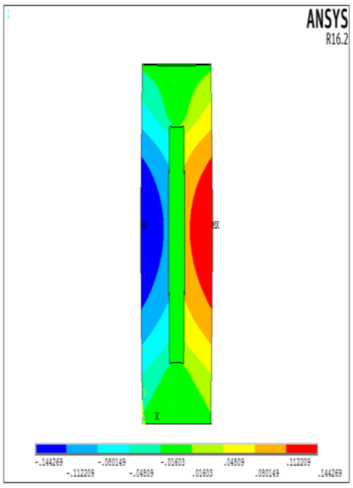

Figure-17. Lateral displacement-case3.

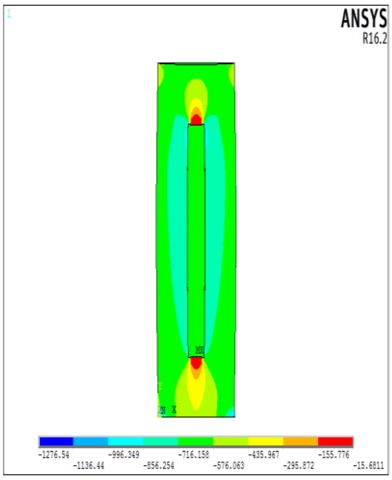

Figure-18. Axial stress-case3.

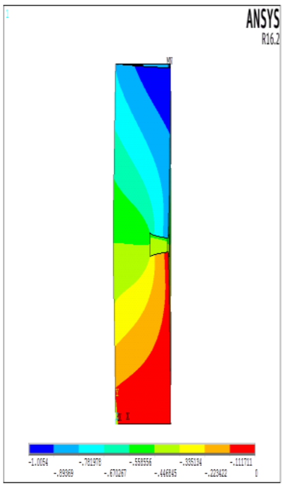

Figure-19. Axial displacement-case4.

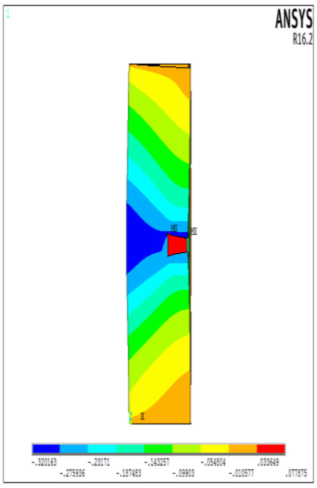

Figure-20. Lateral displacement-case4.

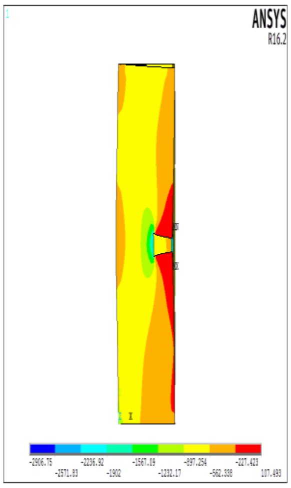

Figure-21. Axial stress-case4.

Figure-22. Axial displacement-case5.

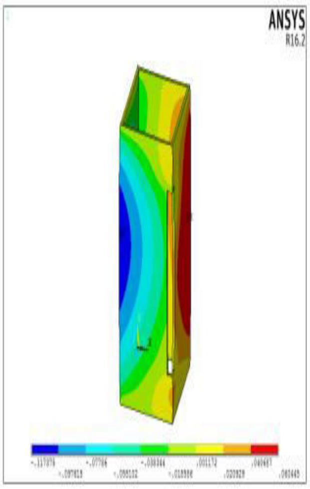

Figure-23. Lateral displacement-case5.

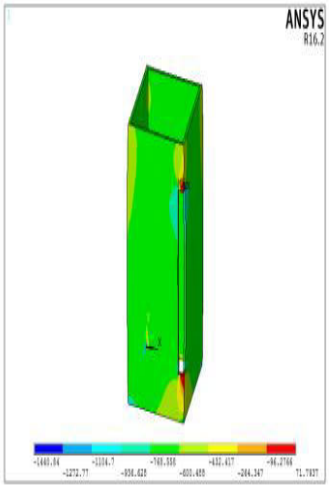

Figure-24. Axial stress case5.

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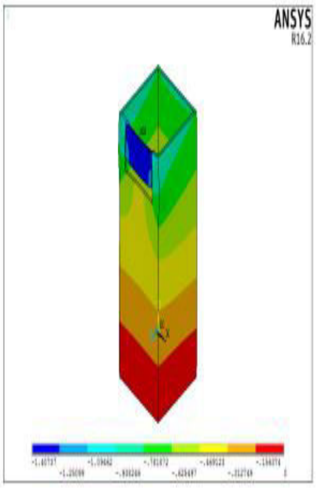

Figure-25. Axial displacement-case 6.

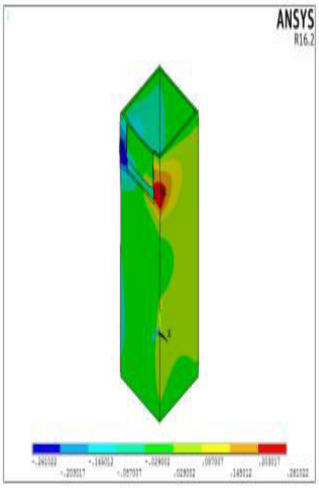

Figure-26. Lateral displacement - case 6.

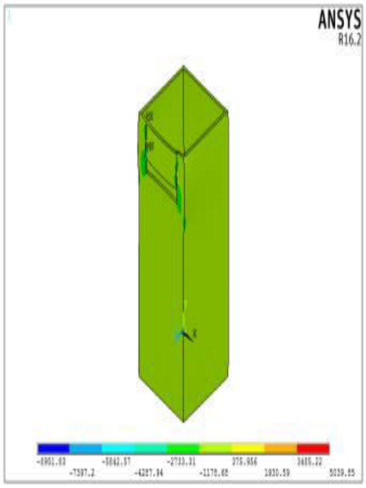

Figure-27. Axial stress - case 6.

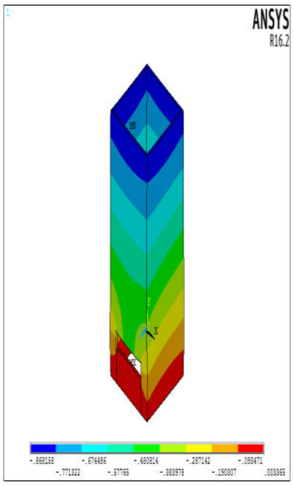

Figure-28. Axial displacement-case7.

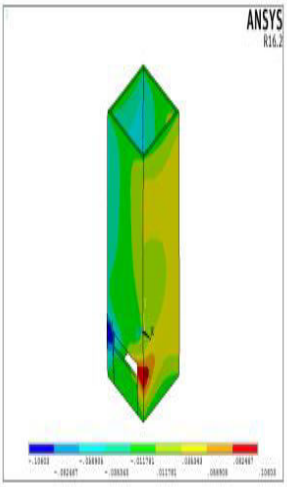

Figure-29. Lateral displacement-case7.

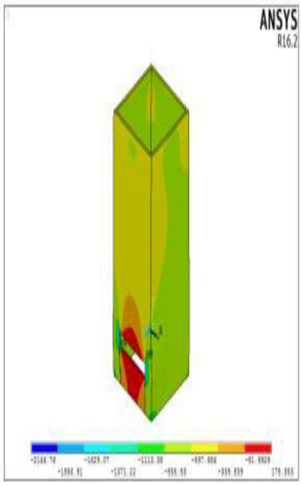

Figure-30. Axial stress-case7.

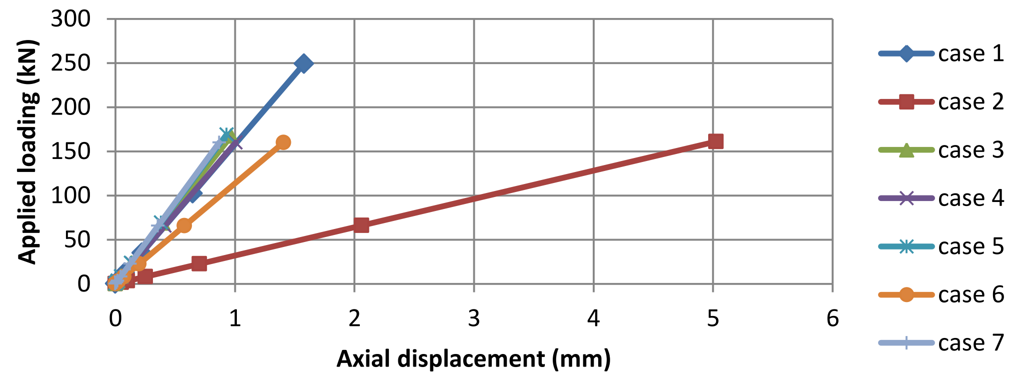

Figure-31. Performance of axial displacement for all cases with applied loading.

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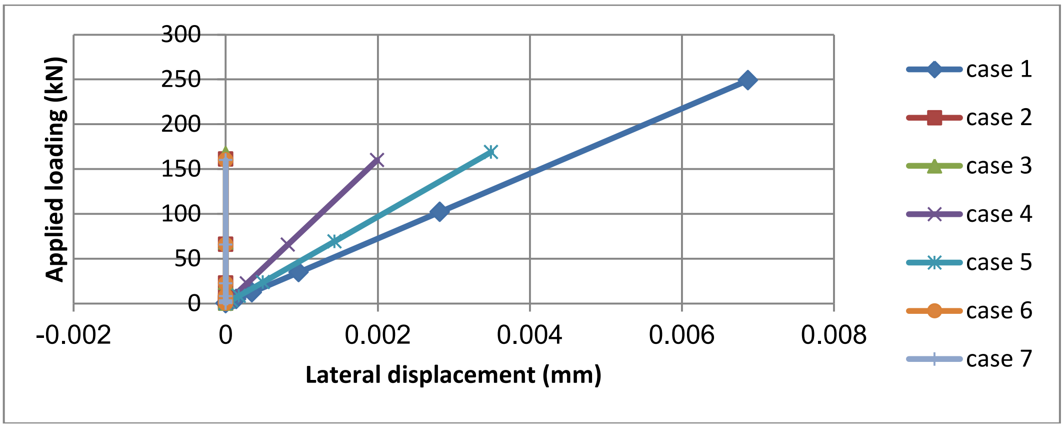

Figure-32. Performance of lateral displacement for all cases with applied loading.

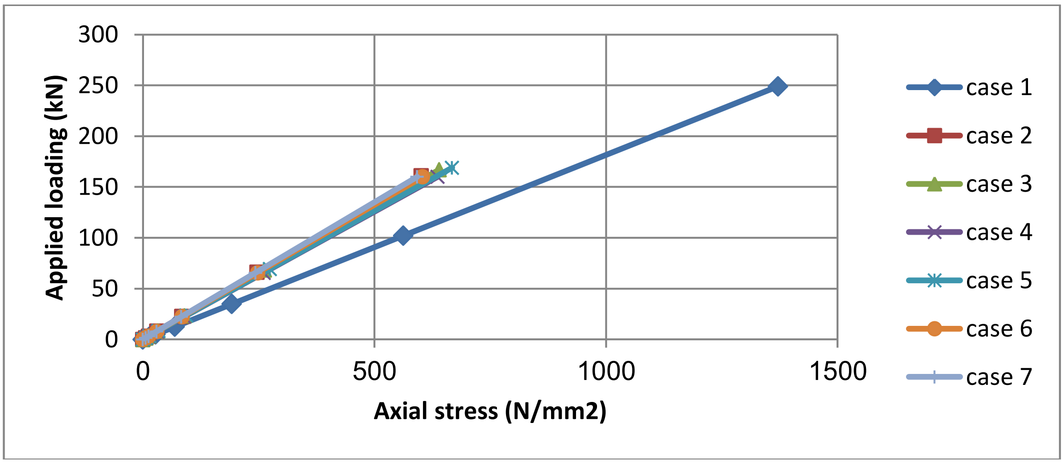

Figure-33. Performance of axial stress for all cases with applied loading.

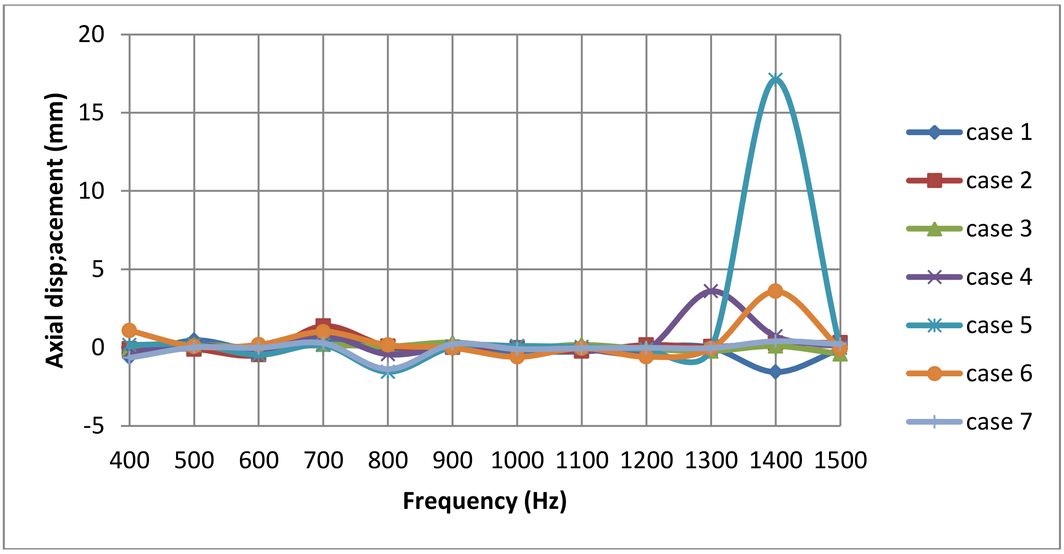

Figure-34. Performance of axial displacement for all cases with applied harmonic loading.

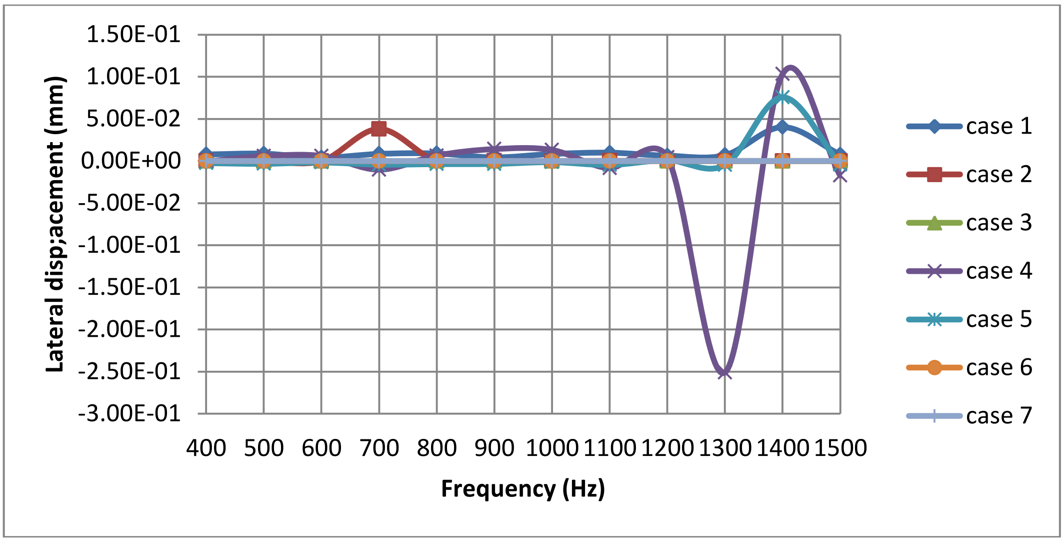

Figure-35. Performance of lateral displacement for all cases with applied harmonic loading.

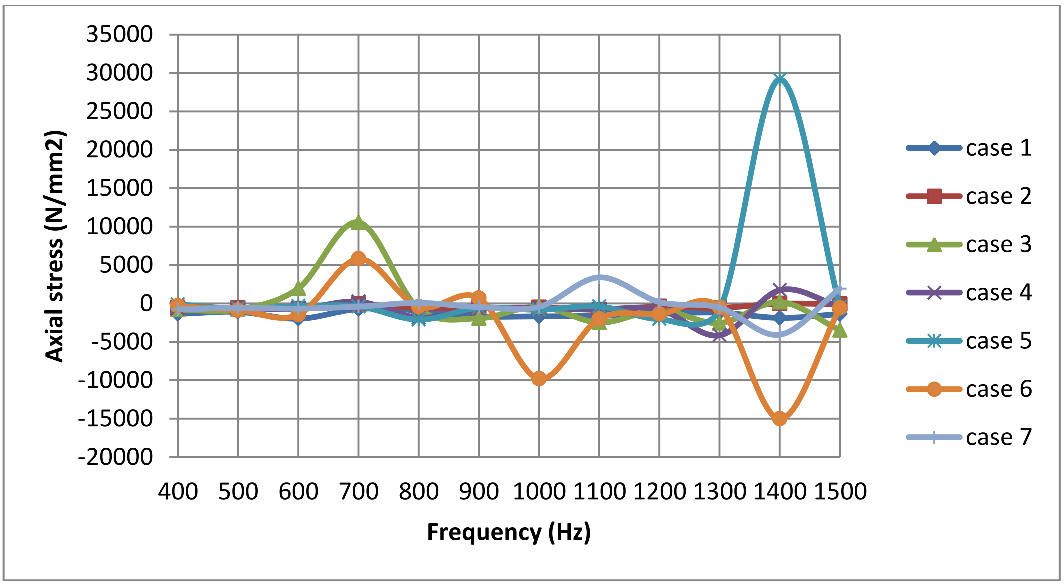

Figure-36. Performance of axial stress for all cases with applied harmonic loading.

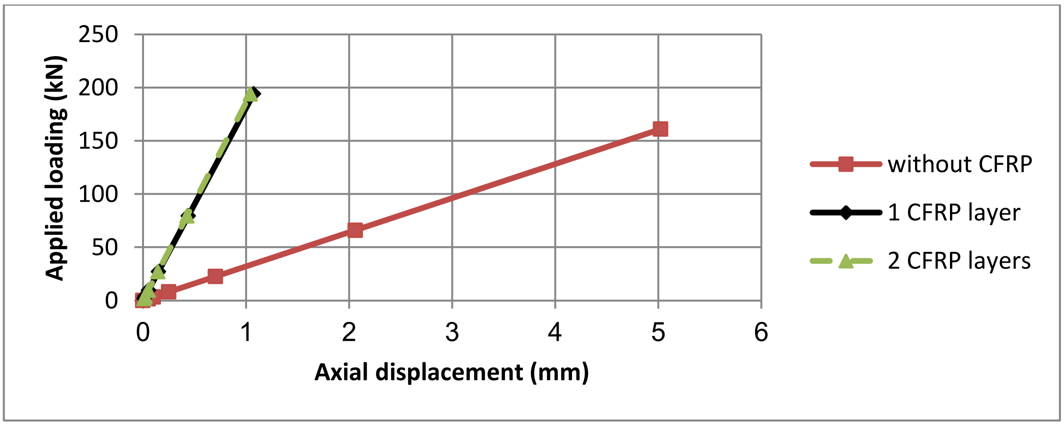

Figure-37. Performance of axial displacement for case2 with and without CFRP under applied static loading

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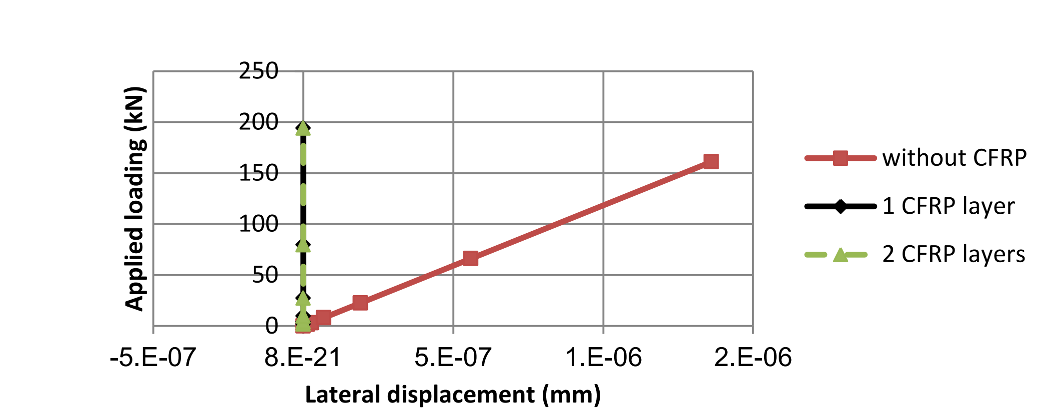

Figure-38. Performance of lateral displacement for case2 with and without CFRP under applied static loading.

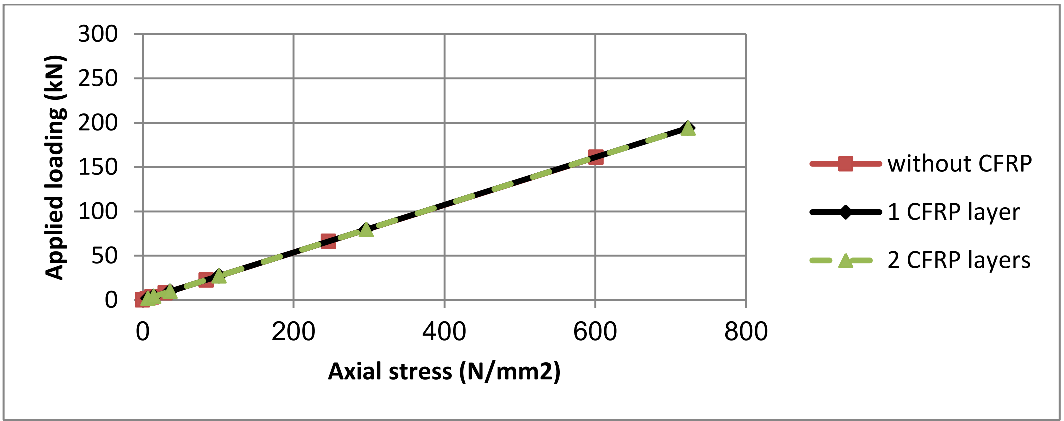

Figure-39. Performance of axial stress for case2 with and without CFRP under applied static loading.

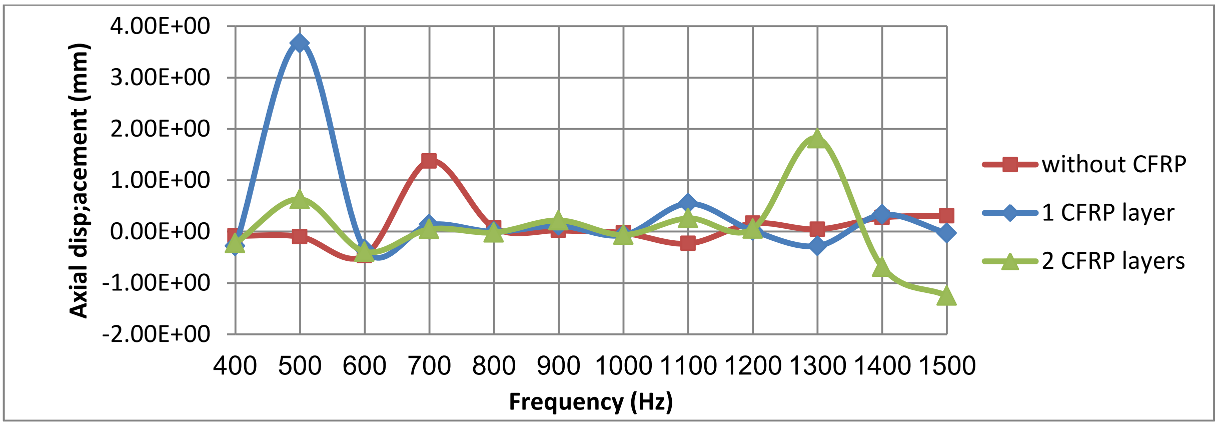

Figure-40. Performance of axial displacement for case2 with and without CFRP underapplied harmonic loading.

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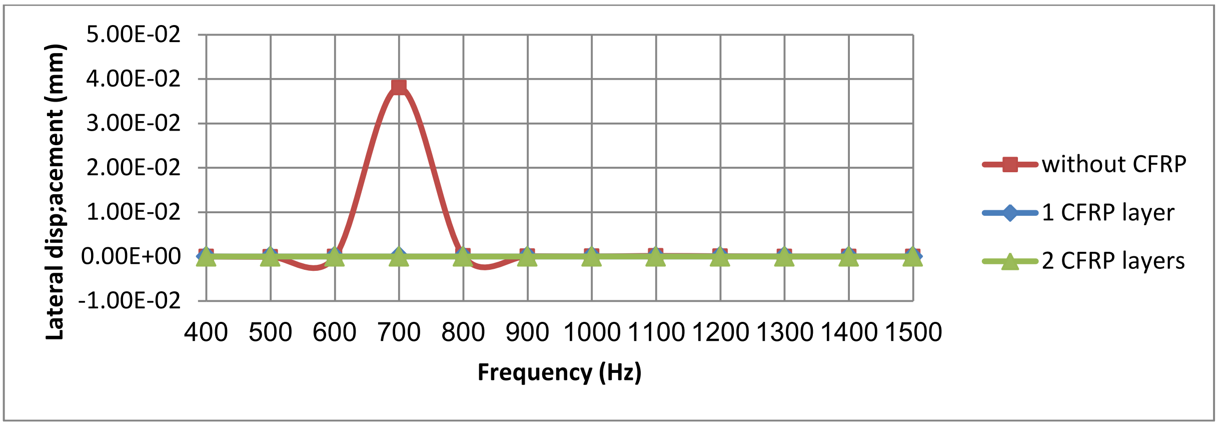

Figure-41. Performance of lateral displacement for case2 with and without CFRP underapplied harmonic loading.

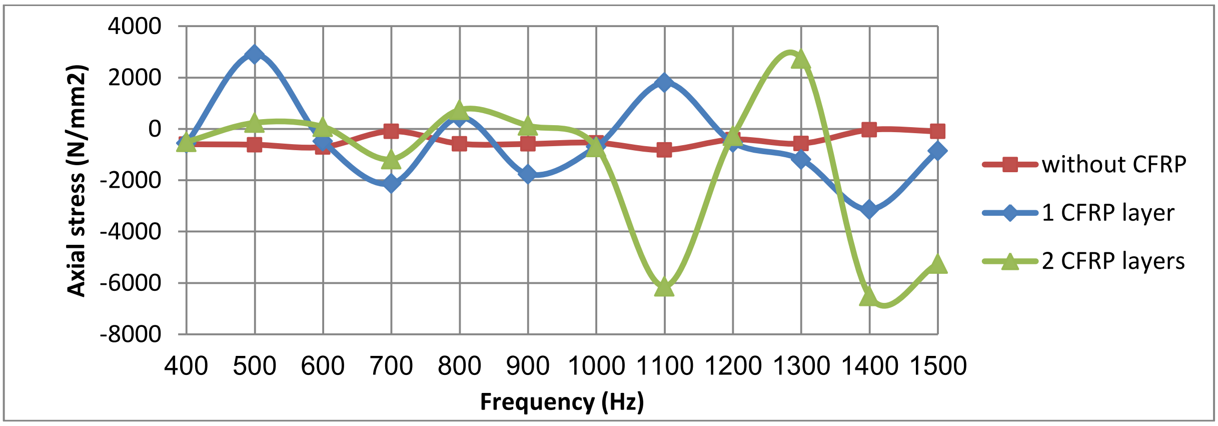

Figure-42. Performance of axial stress for case2 with and without CFRP under applied harmonic loading.

DISCUSSIONS AND CONCLUSIONS

Based on the results from numerical solutions by ANSYS, the following points are drawn for static and dynamic loading:

a) The strength capacity of column as axial stress, axial and lateral displacements are checked first in model case 1 under static loading based on AISC-360-16 and evaluated with the principles of strength of materials.
b) The displacement of control column caused by applied failure load is greater than the serviceability of the column. The displacements and the applied loadings compared with that obtained by [1] show reasonable agreements with the analysis results.
c) The lateral displacement due to applied loading for columns was small which indicated that no buckling occurs.
d) In case of static loading, the static axial displacement at failure load for all columns are greater than the displacement calculated by using the fundamental of strength of materials because of in model the applied loadings are failure load.
e) In case of harmonic loading, the maximum axial and lateral displacements and axial stresses of the columns occur at different frequencies but still in the high frequency range. This difference is occurred because of the different frequencies with constant applied loading (amplitude) and different time (sine wave) make the applied force is different as frequencies are different and hence the displacements and all unknowns become varies with time and frequency.
f) The frequency that caused maximum axial and lateral displacements is not equal in different deficient column locations. This is because the deficient contribute to some amount of displacements at that location of columns.
g) The presence of CFRP around the deficient gave great results in reduction of axial displacement and lateral buckling displacement, i.e. bonding of CFRP sheets recovers the lost strength due to deficiency.
h) The displacements due to harmonic loading are almost more than that for static analysis and over the serviceability requirements.

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