Jordan Journal of Civil Engineering, Volume **16**, No. **2, 2022**

Numerical Investigation of CFRP-strengthened Circular Concrete Columns under Transverse Impact Loading

Maysa Adel Abu Sosain[1)*], Raizal S.M. Rashid [1)] and Mohamed El-Zeadani [1)]

[1)] Department of Civil Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.
* Corresponding Author. E-Mail: maysa_sosain@yahoo.com (M. Abusosain)

ABSTRACT

Bridge columns are continuously exposed to major damage due to vehicle collisions and such collisions can result in disastrous consequences. Composites such as carbon fibre-reinforced polymer (CFRP) provide improved performance under impact load. As such, the objective of this research is to conduct a thorough numerical analysis of four main circular RC column models under impact load using ABAQUS/Explicit. The columns had a 5.18-m height and a 0.61-m diameter and were comprised of both unstrengthened and CFRP-strengthened columns with different types of CFRP sheet wrapping (half, partially and fully wrapped). The impact of an 8-ton truck at two different speeds (60 and 90 km/hr) was investigated and the lateral displacement and impact force were measured. The numerical results showed good performance of RC columns with CFRP sheets as opposed to bare columns, which was indicated by the reduction in maximum lateral displacement and higher impact force of the former as compared to the latter. Overall, the results show the potential of using CFRP wrapping to improve the performance and increase the stiffness of RC columns against impact load.

KEYWORDS: RC columns, CFRP strengthening, Finite element model, Impact load, ABAQUS.

INTRODUCTION

In civil engineering structures, columns are particularly important and their failure may cause progressive collapse and ultimately disastrous consequences (Demartino et al., 2017; Kadhim et al., 2018; Kadhim et al., 2019). Impact actions (e.g. vehicle collisions) can cause significant hazards to bridges or building structures (Demartino et al., 2017; Cai et al., 2018). As such, the resilient design of columns to withstand accidental actions has received well-deserved popularity in recent years and is increasingly being requested by new infrastructure clients. As for existing structures, strengthening of columns has become necessary to avert accidental damage due to impact actions. One way to achieve effective strengthening of reinforced concrete (RC) structures is by using fiber-reinforced polymer (FRP) sheets/plates (Amran et al., 2020). Similarly, FRP confinement of RC columns can prove to be an ideal solution for enhancing their characteristics (Sharma et al., 2013; Benzaid et al., 2009). Due to its superior properties, CFRP has been extensively used in the strengthening of existing structures (i.e., beams, columns and slabs) (Fujikake et al., 2017; Kadhim et al., 2018; Roudsari et al., 2018; Batuwitage et al., 2018; El-zeadani et al., 2019). Thorough research has been carried out since the early 1990s to retrofit existing RC structures using externally bonded FRP composites. The response of CFRP-confined RC columns to static actions has been widely investigated in previous experiments (Xiao and Wu, 2000; Smith et al., 2010; Wang et al., 2012). More research is needed, however, to investigate the response of such confined columns to extreme loads such as impacts, blasts and earthquakes (Pham and Hao, 2017). Applications of CFRP show their effectiveness in the structural elements of building structures (El-Zeadani et al., 2019), military facilities (Ray et al., 2001) and long-span bridges (Miller et al., 2001). Unfortunately, research on the structural performance of CFRP-confined concrete against impact load is still limited.

Received on 7/12/2021.
Accepted for Publication on 15/2/2022.

Sha et al. (2015) investigated by numerical models of bridge piers the effect of CFRP composites to protect reinforced concrete piers from barge impact loads. Impact force and pier action are examined with and without CFRP strengthening. The results reveal that a CFRP composite-strengthened bridge pier has a better impact resistance capacity than an unstrengthened pier. Kiran et al. (2021) investigated the process for predicting the RC moment-resisting frames under blast loading by utilizing a multi-mode adaptive pushover (MADP) analysis. The suggested procedure's main benefit is that it combines multi-mode and adaptive pushover analysis methodologies, which has never been done before for blast loading. The findings showed that the suggested MADP approach can predict the blast loading demand on RC-MRFs with sufficient accuracy and efficiency. The plating arrangement and number of layers of CFRP plates play an important role in the response of strengthened RC columns to impact loads. Thus far, only limited studies have been conducted on the impact resistance of FRP-stimulated RC structures (Zhang and Hao, 2019), in particular for circular RC columns.

The objective of this research is to investigate the performance of CFRP-strengthened RC columns under transverse impact loading, which is a common cause of structural failure from vehicular collisions. In addition, the role of such strengthening in enhancing collapse behaviour and preventing progressive collapse is investigated. A numerical study of the effect of CFRP strengthening on circular RC columns subjected to vehicular impact at two velocities (60 and 90 km/hr) sheds light on the behaviour of bridge columns without strengthening. In addition, the study assesses the behaviour of CFRP-strengthened full-scale bridge columns with different CFRP plating arrangements (half, partially and fully wrapped CFRP sheets) and the different numbers of CFRP plies The results are given in terms of lateral displacement and maximum impact force and the numerical analysis was performed using ABAQUS/Explicit to arrive at a better understanding of the impact performance of CFRP-strengthened RC columns.

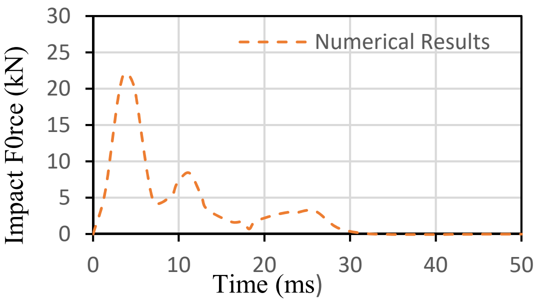
Finite Element Analysis (FEA)

A numerical model for a scaled RC column with impactor was established by using ABAQUS/Explicit. A scaled RC column has been modelled and analyzed under pendulum impact. The results are compared with the pendulum impact test conducted by Zhang et al. (2016) to ensure that the numerical modeling and analysis process is accurate. The dimensions of the rectangular column (a quarter-scale model) were 100 mm x 100 mm x 800 mm (*l* x *w* x *h*) and the full specimen details and experimental setup can be found in Zhang et al. (2016). The boundary conditions for the column were fixed at the bottom (at footing) and pinned to the superstructure at the top. To simulate reality, a mass of 288 kg was added on the top of the column to represent the total mass of the superstructure. Moreover, the column consisted of four 6-mm diameter longitudinal bars (yield strength, f_y = 500 MPa) and 4-mm diameter stirrups (f_y= 300 MPa) spaced at 40 mm. The weight of the steel impactor was 300 kg with a velocity of 0.64 m/s with horizontal impact at the middle of the scaled column.

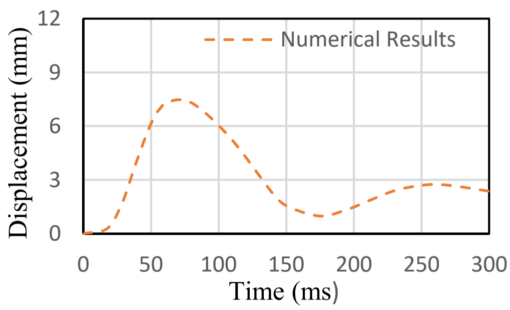
Fig. 1 shows the results of the lateral displacement and impact force from the pendulum test. The peak impact force and peak lateral displacement were 24.7 kN and 6.7 mm, respectively, while the corresponding results in the experimental test were 22 kN and 7.5 mm, respectively, making the difference between the numerical and experimental values at about 12.2% and 10.7% for the peak impact force and peak lateral displacement, respectively. As such, a relatively good correlation between the numerical and experimental results is observed.

Geometry and Material Characterization of the Tested Column

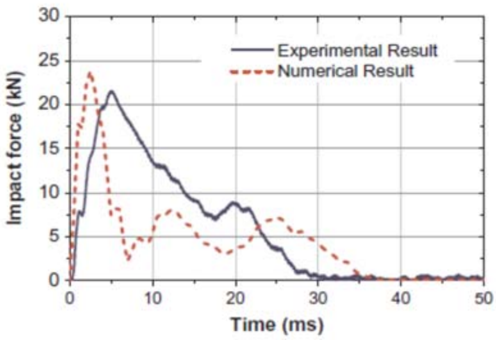
The cylindrical columns considered as part of this research had a height of 5180 mm and a diameter of 610 mm. The columns were reinforced with a total of eight longitudinal steel bars of 22-mm diameter and 6.35-mm diameter stirrups were spaced at 150 mm along the height of the column as given by Sharma et al. (Sharma et al., 2014). The concrete's compressive strength was 40 MPa, while the yield strength of the longitudinal steel and stirrups was 427 MPa and 416 MPa, respectively. The elastic modulus for concrete and steel reinforcement was 30 GPa and 204 GPa, respectively, while the Poisson's ratio for the concrete and reinforcement was 0.2 and 0.3, respectively. The CFRP sheets were installed following Abdel-Naser et al. (2017), who used a variety of plies (1 to 4) of CFRP with a thickness of 6 mm. A 6-mm thickness was seen to give better performance and reduce the number of CFRP plies required when compared to other CFRP thicknesses (i.e., 2, 3 or 4 mm) (Abdel-Naser et al., 2017). This research investigated the performance of reinforced concrete (RC) columns, wrapped with CFRP and subjected to a transverse impact load to determine the effect of the layer number of CFRP on the stiffness of RC columns and the effect of an external accident on concrete columns confined with CFRP (Takla et al., 2020). The CFRP plating arrangements considered in this research included half-wrapping (4 plies) of the RC columns from the column base to mid-height, partial wrapping (4 plies) of the CFRP sheets commencing from the base of the column, where the width of the CFRP sheets was 250 mm and the spacing between different partial wraps (4 plies) was 300 mm and full wrapping of the RC column with one ply of CFRP. This research aimed to find out which of the previous models is equivalent to full wrapping of the RC columns The material properties for the CFRP sheets used are as in Abdel-Naser (2017). For non-linear FE analysis, the concrete material model can play an essential role in predicting the strength of concrete. In this research, the model chosen was the Concrete Damage Plasticity (CDP) model, which represents the brittle-cracking model (Mokhatar and Abdullah, 2012; Niza et al., 2012). The compressive and tensile behaviour details for the CDP model are as given in Niza (2012). The modeling of concrete went through two steps. In the initial step, the elastic modulus and Poisson's ratio were defined, while the CDP model was used in the second step to model the non-linear behaviour of the stress-strain relationship. Furthermore, the dilation angle chosen was 38°, the eccentricity was set to 1 and the ratio of the initial equiaxed strength to the initial uniaxial strength was 1.12 (Niza et al., 2012; Minh et al., 2021). In addition, the main steel reinforcement and the stirrups were defined as elastic-perfectly plastic materials by defining their elastic modulus and yield strength. As for the CFRP plate, a linear elastic material model was adopted in the FE analysis.



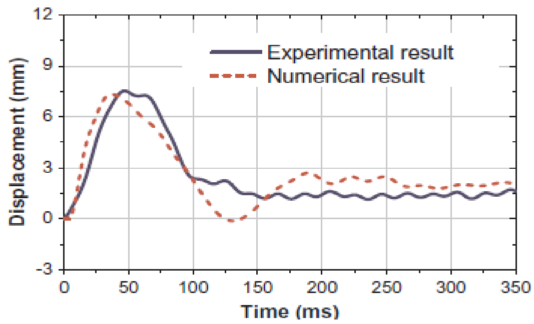
(a) Impact force for the validation model



(b) Lateral displacement for the validation model



(c) Impact force for Zhang et al., 2016



(d) Lateral displacement for Zhang et al., 2016

Figure (1): Results for validation model

Description of the Finite Element Model (FEM)

The RC circular column investigated in this paper was modelled using a three-degree of freedom (8-nodes) solid element (C3D8R) available in the ABAQUS/Explicit library (Kadhim and Adheem, 2018). The top boundary condition for the column investigated in this research was modelled as pinned, while the bottom boundary condition was chosen as fixed. The simplified vehicle model proposed by Demartino et al. (2017) was used to model the mass of the truck as a rigid body with a reference point. The test truck was represented by a rectangular steel block having a size of 0.58 m x 0.80 m x 0.20 m (Demartino et al., 2017), weighing 8 tons and acting at 1.5-m from the bottom of the column. A 1.5-m distance was chosen to represent the point of impact of a vehicle on a bridge column (El-Tawil et al., 2003). Moreover, the vehicular impact speeds considered in this research were 60 km/hr and 90 km/hr. As for the reinforcement, a two-node linear displacement (T3D2) truss element was employed to model the internal reinforcement (main reinforcement and stirrups). The material model used for the internal steel reinforcement was a 3D deformable wire, whereas a shell element (S4R) was employed to represent the CFRP (Kadhim and Adheem, 2018). Furthermore, an embedded region interaction was used in the FE analysis between the concrete and reinforcement steel, while a tie interaction was set between the concrete and the CFRP plate. The contact property between the concrete and CFRP plate was surface-to-surface and the contact property was chosen as a tangential contact. The friction formulation used was a penalty with a friction coefficient of 0.15. As for the interaction (contact type) between the column and test truck, a general contact was chosen (type: dynamic, explicit). As for the convergence criteria used in the FE analysis, the default criteria set by ABAQUS/Explicit were adopted. In total, twenty models were investigated under impact load and the models were labelled to allow easy identification. As such, from the far left, the numbers ply-1, ply-2, ply-3 and ply-4 denoted the number of CFRP plies (Fig. 2). The letters H, P and F (half-wrapping, partial wrapping and full wrapping, respectively) represent the height of CFRP. The last letter C represents the column (Hadi and Widiarsa, 2012). For instance, model 2HC60 had two plies of CFRP with half-wrapping and was subjected to an impact velocity of 60 km/hr.

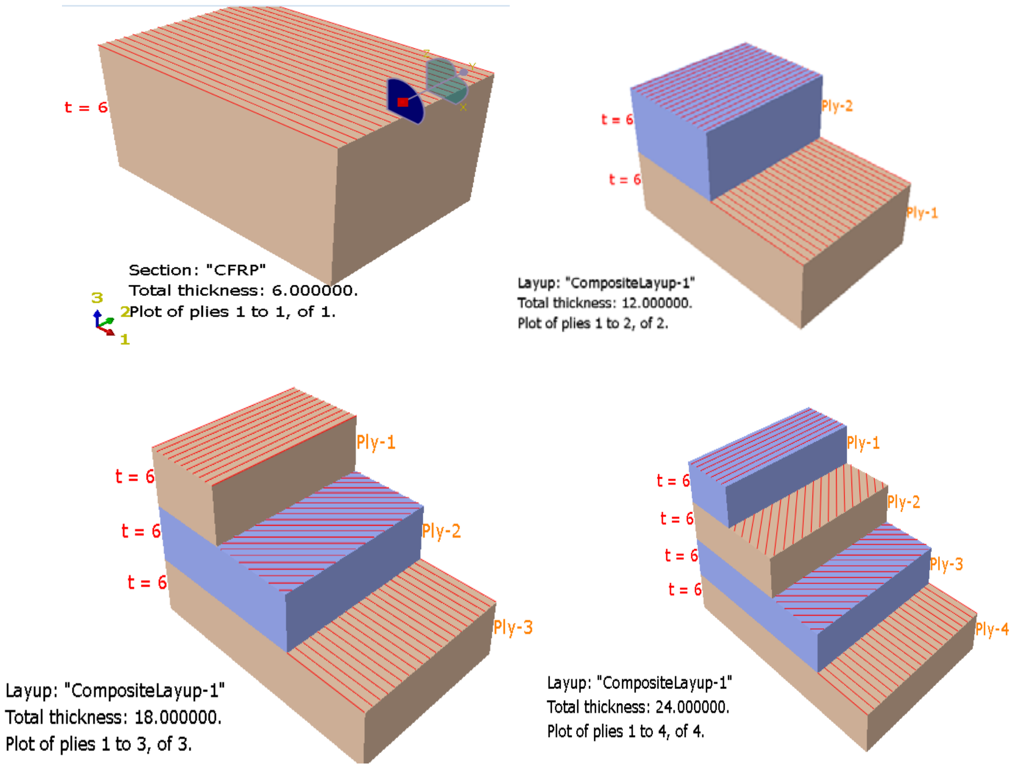
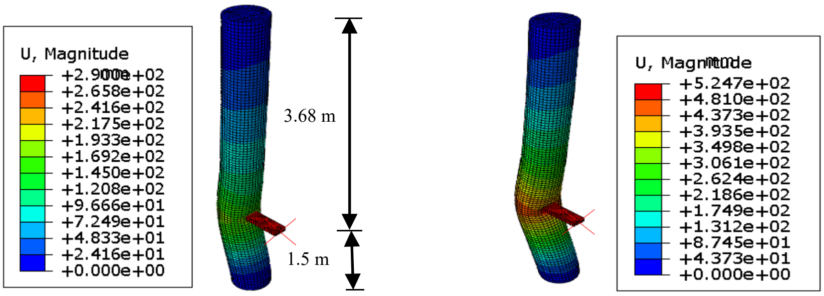


Figure (2): No. of plies of CFRP

Numerical Simulation Results for Lateral Displacement and Impact Force

Lateral Displacement Time Histories

The displacement *versus* time graph as derived from the time history analysis for the four main models was determined and later compared to the lateral displacement at peak value under two velocities (60 and 90 km/hr). The displacement-time histories comprise the ascent, descent and damped vibration stages. As shown in Fig. 3, the maximum lateral displacement of a bare column, when exposed to an impact velocity of 90 km/hr, was 524.7 mm, while the maximum lateral displacement caused by a 60 km/hr velocity was 290.2mm.



a) 0C60 (b) 0C90

Figure (3): Bare column displacement (mm) for velocities: (a) 60 km/hr and (b) 90 km/hr

As for the CFRP half-wrapped columns (Fig. 4), the results are given in Table 1 and the columns were strengthened with either 1, 2, 3 or 4 plies of CFRP sheets (Fig. 4). Strengthening the columns had a marked influence on the lateral displacement. For instance, for the column strengthened with 4 plies and subjected to an impact velocity of 60 km/h, the maximum lateral displacement was 64.5 mm, which is considerably smaller than that of the bare column (290.2 mm), showing an enhancement of the RC column by using CFRP sheets and minimizing the damage to the bridge column. As for the half-wrapped column subjected to an impact velocity of 90 km/hr, the lateral displacement was much smaller than that of the bare column, where a reduction of 58.55%, 77.07%, 77.57% and 79.09% was seen for 1HC90, 2HC90, 3HC90 and 4HC90, respectively. One salient fact that can be deduced from the results is that the greater the number of CFRP plies, the greater the reduction in lateral displacement when compared to the bare column. This is due to the enhanced stiffness provided by the additional plies of CFRP sheets. Similar observations were made by Alam et al. (2015) when half-wrapping was employed in columns subjected to vehicular impact.

Table 1. Lateral displacement results for half-and partial wrapping under two velocities (60 and 90 km/hr)

	60 km/hr		**90 km/hr**	
No. of CFRP plies	**Max. Displacement (mm)**		**Max. Displacement (mm)**	
	Half-wrapping	**Partial wrapping**	**Half-wrapping**	**Partial wrapping**
1 Ply	114. 9	101.7	217.5	220.10
2 plies	72.25	96.63	120.3	198.83
3 plies	69.41	91.27	117.7	195.294
4 plies	64.5	90.804	109.4	193.496

As for the third model (Fig. 5), where partial wrapping of CFRP was applied to the RC columns, the lateral displacement results are also given in Table 1. Four plies of partial wrapping caused a reduction in the peak lateral displacement by 68.71% and 63.12% for the two impact velocities of 60 and 90 km/hr, respectively, as compared to the bare columns. Furthermore, from the findings in Table 1 for the partially wrapped columns, it can be seen that there was no great difference in the reduction of lateral displacement between the cases of the different numbers of plies and this could mean that partial wrapping does not enhance the stiffness of the RC columns considerably when varying the number of CFRP plies.

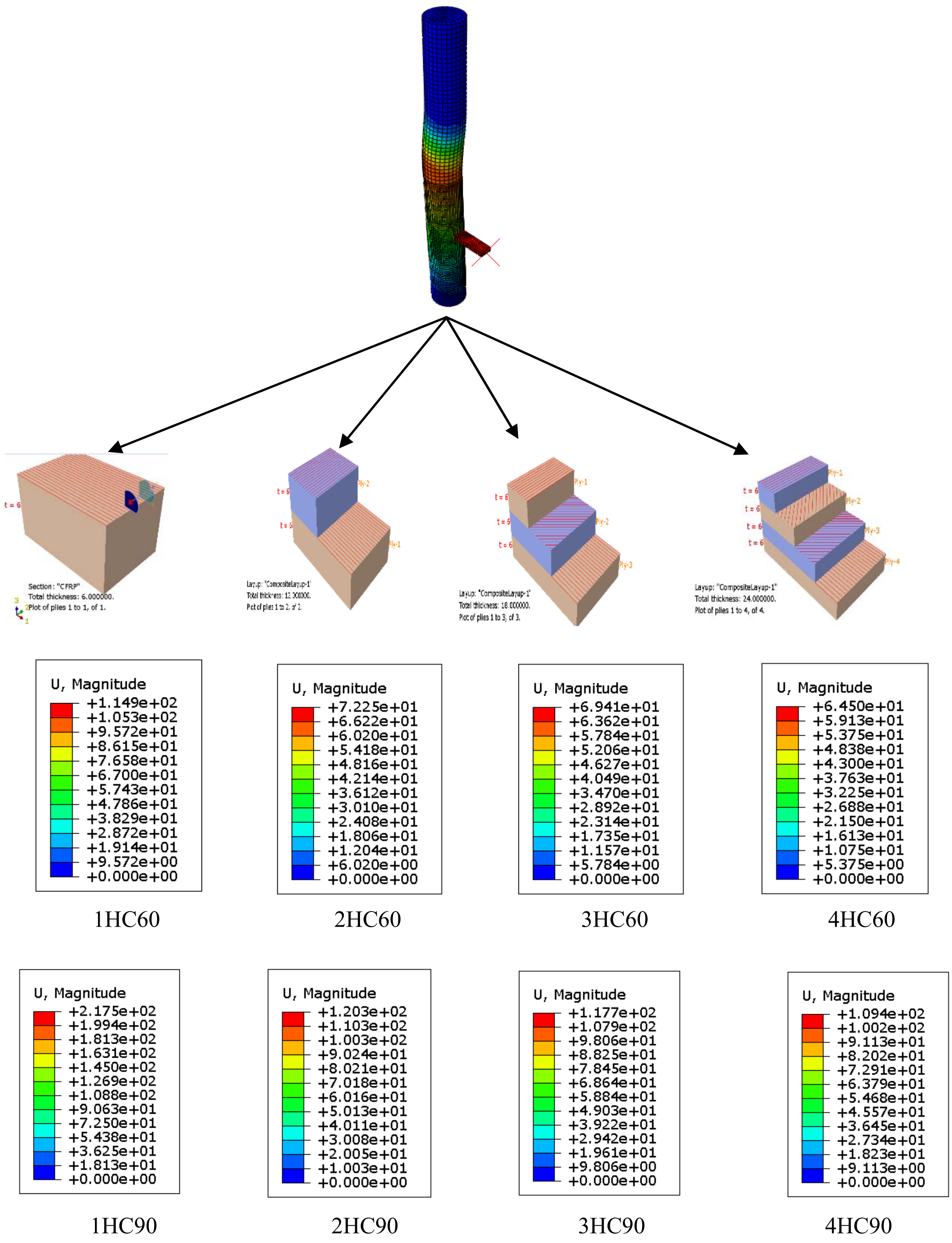


Figure (4): Half-wrapping of CFRP under velocities (60 and 90 km/hr)

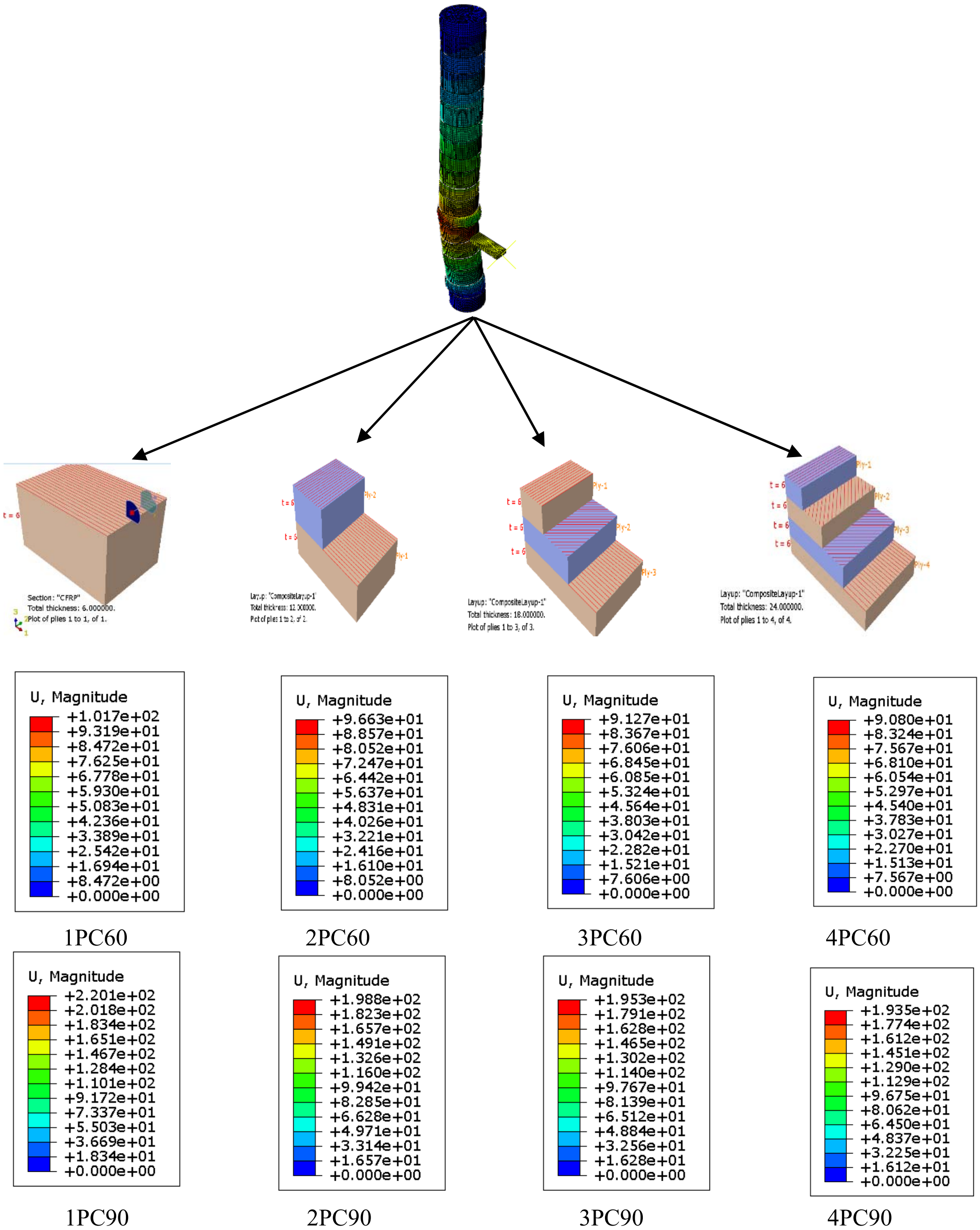
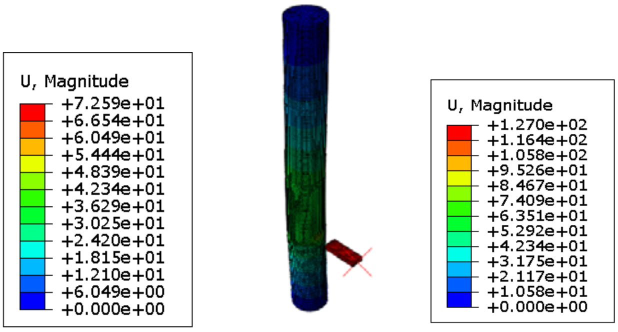


Figure (5): Partial wrapping of CFRP under velocities (60 and 90 km/hr)

Moreover, it was noted that for the CFRP-confined concrete columns, the maximum lateral displacement point shifted up at the end of the CFRP-sheets, indicating more damage in that region. For instance, the maximum lateral displacement in the bare column occurred at the level of the impact point. However, for the half-wrapped columns, the peak lateral displacement shifted the plastic hinge above the end of the CFRP piles. As for the partially wrapped columns, due to the highly intensive stresses, these stresses propagated from the impact point to the area between the strips of CFRP, causing large damage in this region. This behaviour can be considered similar to that of the unstrengthened column.

Finally, the fourth model (full wrapping using one CFRP ply) was also tested under two velocities (60 and 90 km/hr) as shown in Fig. 6. The peak displacement results for the fully wrapped columns were 72.59 mm and 127.01 mm under a velocity of 60 km/hr and 90 km/hr, respectively. Compared to those of the bare columns, the reduction, in this case, was 75% and 75.8% for 60 km/hr and 90 km/hr impact velocity, respectively. Again, the reduction in lateral displacement was due to enhanced column stiffness as a result of CFRP wrapping and similar findings were observed by Alam et al. (2015).

Figs. 7 and 8 summarize the lateral displacement time history under the two velocities (60 and 90 km/hr) for all models considered. Moreover, for the bare columns, the maximum lateral displacement occurred at a slightly later time compared to the CFRP-strengthened columns; that is, the ascent stage for the bare columns took more time than for the plated columns and this happens to agree with the results observed by Alam et al. (2016) and Batuwitage et al. (2018).



1FC60 1FH90

Figure (6): Full wrapping of CFRP under velocities of 60 & 90 km/hr

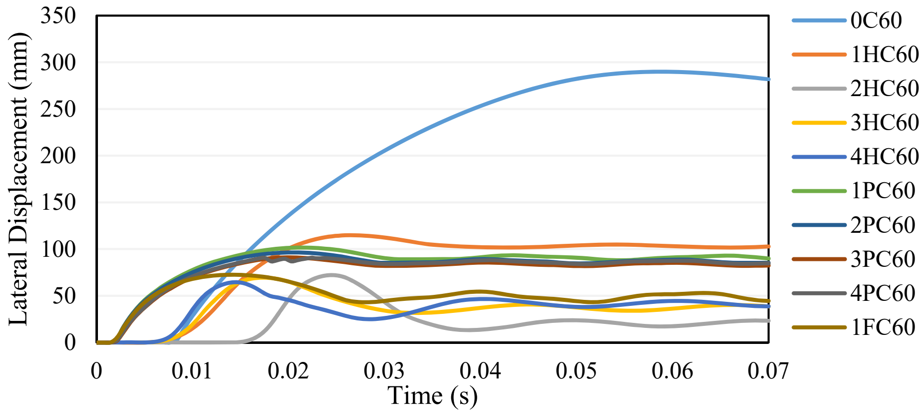


Figure (7): Lateral displacement-time history under 60 km/hr velocity

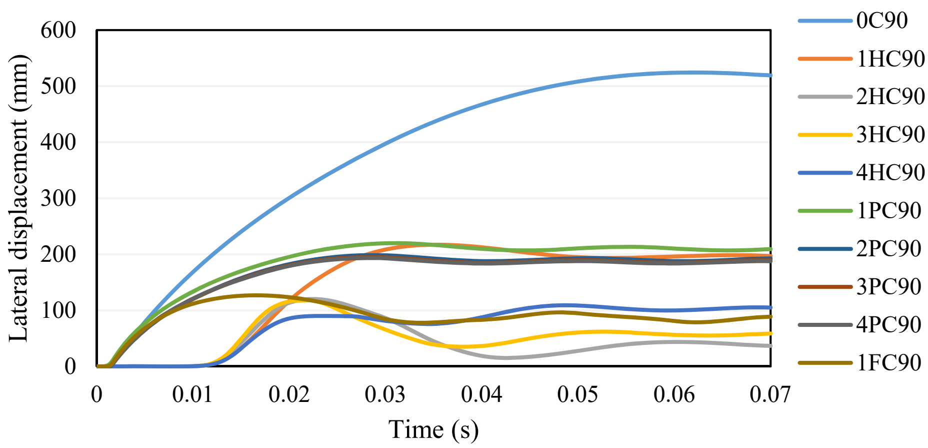


Figure (8): Lateral displacement-time history under 90 km/hr velocity

Impact Force Time Histories

Impact resistance and impact response can be estimated from the impact force. The impact force-time history consists of three phases, where phase one takes place from the beginning of the test up to the first peak. As for the second phase, due to its relatively long duration (so-called plateau), most of the impact energy is dissipated within this phase. In the third and final phase, the impact force decreases to zero gradually indicating that all impact energy has been dissipated (Kadhim and Adheem, 2018) and this is known as the unloading phase. For the first model, in the bare column (Fig. 3), the impact force on the bare RC column under a velocity of 60 km/hr was 319.11 kN (0C60), while that for the bare column under a velocity of 90 km/hr was 438.48 kN (0C90). As for the second model (Fig. 4), where half-wrapping of CFRP was employed, the impact force results are given in Table 2. As the impact velocity increased from 60 to 90 km/hr, the peak impact force when 4 plies of CFRP were used rose from 1018.25 kN to 1502.29 kN. Furthermore, the application of more plies of CFRP resulted in a higher impact force due to the higher stiffness of the RC columns for both velocities considered. For instance, the enhancement in impact force due to 1, 2, 3 and 4 plies of CFRP half-wrapping as compared to the bare columns was 121.1%, 124.8%, 197.24% and 219.1%, respectively, for a 60-km/hr impact velocity and 154.4%, 189.6%, 238.9% and 242.61%, respectively, when a 90-km/hr impact velocity was applied. This enhancement in impact force due to half-wrapping was observed by Alam et al. (2015) as well.

Table 2. Impact force for half-and partial wrapping of CFRP under two velocities (60 and 90 km/hr)

No. of plies of CFRP	60 km/hr		90 km/hr	
	Max. impact force, kN		Max. impact force, kN	
	Half-wrapping	Partial wrapping	Half-wrapping	Partial wrapping
1 ply	705.69	633.211	1115.41	781.64
2 plies	717.317	687.65	1269.63	859.1
3 plies	948.532	766.587	1486.05	1031.17
4 plies	1018.15	823.9	1502.29	1115.41

Furthermore, for the third model where partial wrapping of CFRP was used, the impact force results are also shown in Table 2. From the results, the impact force when one ply of CFRP was used was 633.2 kN, while the impact force when four plies of CFRP were used was 823.9 kN at a velocity of 60 km/hr, implying a 30.1% enhancement. As for the 90 km/hr impact velocity, the impact force when one ply and four plies of CFRP were used was 781.64 kN and 1115.41 kN, respectively, implying a 42.7% enhancement. Compared to the partial wrapping results, the enhancement in impact force due to 1, 2, 3 and 4 plies of CFRP wrapping was 98.4%, 115.5%, 140.2% and 158.2%, respectively, for a 60-km/hr impact velocity and 78.3%, 95.9%, 135.2% and 154.4%, respectively, for a 90-km/hr impact velocity. Due to high stress concentrations in the un-plated portions when partial wrapping was used, the enhancement offered by partial wrapping is less than that supplied by half-wrapping when considering the various amounts of plies.

As for the fourth model, the peak impact force results where a single ply of fully wrapped CFRP was used were 686.49 kN and 984.12 kN for 60 km/hr and 90 km/hr impact velocities, respectively. Comparing these results of the fully wrapped columns to those of the bare columns, the percentage increase in the impact force was 115.12% and 124.43% for the 60 km/hr and 90 km/hr velocities, respectively. Figs. 9 and 10 summarize all impact force-time history results under the two velocities (60 and 90 km/hr) for all models where the three phases of the impact force-time history are visible. From the impact force-time histories, it is clear that the first phase (up to the first peak) occurred over a longer time for the half-wrapped columns, regardless of the number of plies and impact speed, as compared to the bare, partially wrapped and fully wrapped columns. Moreover, the bare columns had a longer plateau, indicating energy dissipation, as compared to the strengthened columns.

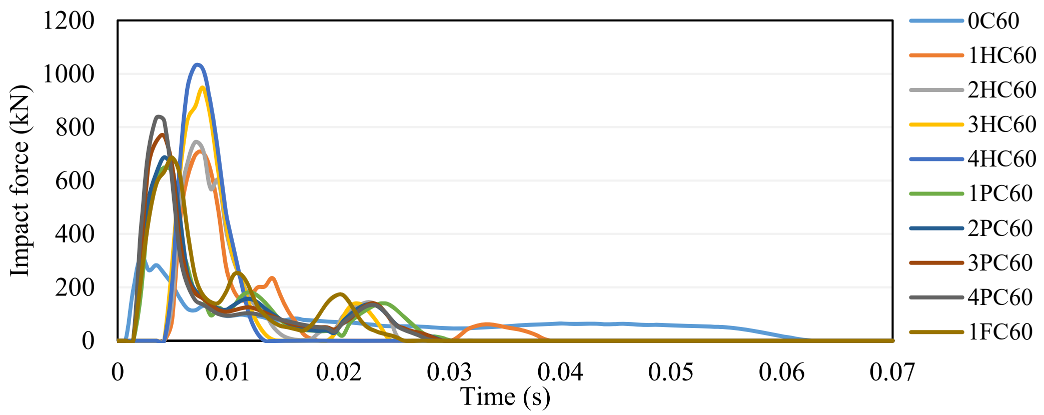


Figure (9): Impact force for all models (60 km/hr velocity)

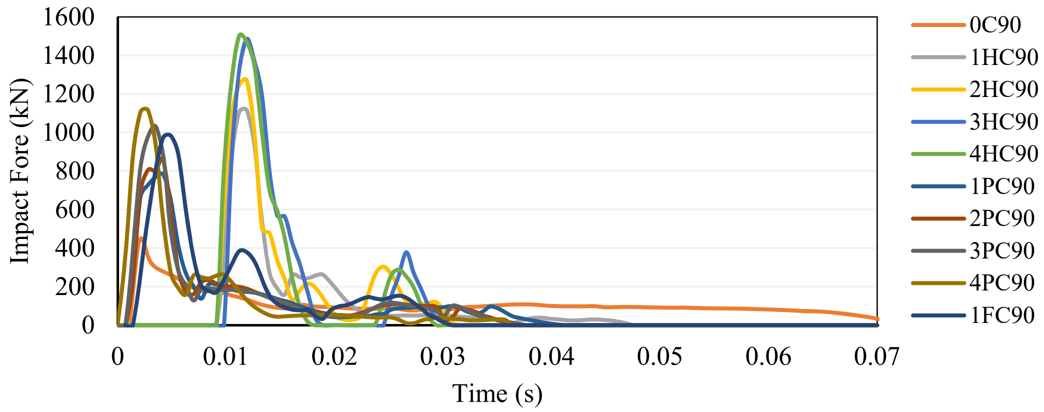


Figure (10): Impact force for all models (90 km/hr velocity)

CONCLUSIONS

The use of CFRP as external reinforcement enhanced the impact force and reduced the lateral displacement for the RC bridge column. Numerical simulation using four main FE models of bare and CFRP-strengthened RC columns was carried out to determine the effect on vehicular impact loading at 1.5-m height. Other key findings from the FE analysis may be summarized as follows:

1. Using CFRP to wrap RC columns can be an ideal way to minimize damage due to impact loads, because CFRP increases the stiffness of the column. More than 60% reduction in maximum lateral displacement was observed when half-wrapping and partial wrapping of the RC columns were employed.
2. Although full wrapping of CFRP sheets for RC columns (1FC) has less effect on lateral displacement, it was seen that 1FC has the same response as 3HC. Therefore, 3HC or 4HC can be adopted as an alternative to the full wrapping of RC columns. This might not be the most cost-effective solution, as 3HC uses more CFRP than 1FC; however, half-wrapping can be adopted when full wrapping of the columns is not feasible.
3. For partial wrapping of CFRP, the lateral displacement reached a certain critical value regardless of whether more plies were added. The lateral displacement did not decrease below this critical value indicating that the confinement of CFRP strips is weak.
4. Half-wrapping can be a better alternative to partial wrapping when considering strengthening circular RC columns. This is because of the accumulation of stresses between partially wrapped CFRP sheets.
5. There are no significant advantages to increasing the number of carbon fiber plies to more than four.

Recommendations

1- Numerical studies considering both axial and transverse loads can be conducted as well to see the effect of different FRP plating arrangements on the response of the columns.

2- The effects of different types of FRP material on the resulting lateral displacement and impact force in the strengthened columns are recommended to be investigated.

Acknowledgements

The authors acknowledge the support of the Department of Civil Engineering, Universiti Putra Malaysia (UPM) while carrying out this research.

Conflicts of Interest: The authors have no conflicts of interest.

REFERENCES

Demartino, C., Wu, J., and Xiao, Y. (2017). "Experimental and numerical study on the behavior of circular RC columns under impact loading". Procedia-Eng., 199, 2457-2462. https://doi.org/10.1016/j.proeng.2017. 09. 386.

Kadhim, M.M.A., and Wu, Z., and Cunningham, LS. (2018). " Experimental study of CFRP-strengthened steel columns subject to lateral impact loads". Compos. Struct., 185, 94-104. https://doi.org/10.1016/j. compstruct.2017.10.089.

Kadhim, M.M.A., Wu, Z., and Cunningham, L.S. (2019). "Numerical study of full-scale CFRP-strengthened open-section steel columns under transverse impact". Thin-Walled Struct., 140, 99-113. https://doi.org/ 10.1016/j.tws.2019.03.034.

Cai, J., Ye, J., Bin, Chen, Q.J., Liu, X., and Wang, Y.Q. (2018). "Dynamic behaviour of axially-loaded RC columns under horizontal impact loading". Eng. Struct., 168, 684-697. https://doi.org/10.1016/j.engstruct. 2018.04.095.

Do, T.V., Pham, T.M., and Hao, H. (2018). "Dynamic responses and failure modes of bridge columns under vehicle collision". Eng. Struct., 156, 243-259. https://doi.org/10.1016/j.engstruct.2017.11.053.

Harik, I.E., Shaaban, A.M., Gesund, H., Valli, G.Y.S., and Wang, S.T. (1999). "United States bridge failures 1951-1988". J. Perform. Constr. Facil., 4, 272-277.

Kim, Y.J., Green, M.F., and Fallis, G.J. (2008). "Repair of bridge girder damaged by impact loads with prestressed CFRP sheets". J. Bridge Eng., 13, 15-23. https://doi.org/10.1061/(ASCE)1084-0702(2008) 13:1 (15).

Ibrahim, A.M., and Mahmood, M.S. (2009). "Finite element modeling of reinforced concrete beams strengthened with FRP laminates". Eur. J. Sci. Res., 30, 526-541.

Mugahed Amran, Y.H., El-Zeadani, M., Raizal Saifulnaz, M.R., Alyousef, R., Alabduljabbar, H., Alrshoudi, F. et al. (2020). "RC beam strengthening using hinge and anchorage approach". Results Mater., 5, 100047. https://doi.org/10.1016/j.rinma.2019.100047.

Sharma, S.S., Dave, U.V., and Solanki, H. (2013). "FRP wrapping for RC columns with varying corner radii". Procedia-Eng., 51, 220-229. https://doi.org/10.1016/j. proeng.2013.01.031.

Benzaid, R., Chikh, N. Eddine, and Mesbah, H. (2009). "Study of the compressive behavior of short concrete columns confined by fiber". Arab J. Sci., Eng., 34, 15-26.

Pham, T.M., and Hao, H. (2017). "Axial impact resistance of FRP-confined concrete". J. Compos. Constr., 21, 1-11. https://doi.org/10.1061/(ASCE)CC.1943-5614. 0000744.

Fujikake, K., Soeum, S., and Matsui, T. (2017). "CFRP-strengthened RC beams subjected to impact loading". Procedia-Eng., 210, 173-181. https://doi.org/10.1016/j. proeng.2017.11.063.

Kadhim, M.M.A., Wu, Z., and Cunningham, L.S. (2018). "Loading rate effects on CFRP-strengthened steel square hollow Abdelkarim sections under lateral impact". Eng. Struct., 171, 874-882. https://doi.org/ 10.1016/j.engstruct.2018.04.066.

Roudsari, S., Hamoush, S., Soleimani, S., Abu-Lebdeh, T., and HaghighiFar, M. (2018). "Analytical study of reinforced concrete beams strengthened by FRP bars subjected to impact loading conditions". Am. J. Eng. App. Sci., 2018. https://doi.org/10.3844/ajeassp.2018.

Batuwitage, C., Fawzia, S., Thambiratnam, D., Liu, X., Al-Mahaidi, R., and Elchalakani, M. (2018). "Impact behaviour of carbon fibre-reinforced polymer (CFRP)-strengthened square hollow steel tubes: A numerical simulation". Thin-Walled Struct., 131, 245-257. https://doi.org/10.1016/j.tws.2018.06.033.

Xiao, Y., and Wu, H. (2000). "Compressive behavior of concrete confined by carbon fiber composite jackets". J. Mater. Civ. Eng., 12, 139-146.

Smith, S.T., Kim, S.J., and Zhang, H. (2010). "Behavior and effectiveness of FRP wrap in the confinement of large concrete cylinders". J. Compos. Constr., 14, 573-582. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000119.

Wang, Z., Wang, D., Smith, S.T., and Lu, D. (2012). "CFRP-confined square RC columns. I: Experimental investigation". J. Compos. Constr., 16, 150-160. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000245.

Eid, R., and Paultre, P. (2008). "Analytical model for FRP-confined circular reinforced concrete columns". J. Compos. Constr., 12, 541-552. https://doi.org/10.1061/(ASCE)1090-0268(2008)12, 5(541).

El-Zeadani, M., Saifulnaz, M.R.R., Mugahed Amran, Y.H., Hejazi, F., Jaafar, M.S., Alyousef, R. et al. (2019). "Flexural strength of FRP-plated RC beams using a partial-interaction displacement-based approach". Structures, 22, 405-420. https://doi.org/10.1016/j.istruc.2019.09.008.

Ray, J.C., Velazquez, G.I., Lamanna, A.J., and Bank, L.C. (2001). "Rapidly installed fiber-reinforced polymer (FRP) plates for upgrade of reinforced concrete bridges for the military". High-perform Mater. Bridge, 359-373.

Miller, B.T.C., Chajes, M.J., Mertz, D.R., Hastings, J.N., and Member, S. (2001). "Strengthening of a steel bridge girder using CFRP plates". J. Bridge Eng., 6, 514-522. https://doi.org/10.1061/(ASCE)1084-0702(2001)6.

Alam, I., Fawzia, S., Liu, X.J., and Batuwitage, C.R. (2014). "Dynamic simulation of CFRP-strengthened steel column under impact loading". 23rd Australas. Conf. Mech. Struct. Mater., 1, 9780994152008.

Alam, M.I., Fawzia, S., and Batuwitage, C. (2015). "CFRP-strengthened CFST columns under vehicular impact". Second Int. Conf.-Performance-based Life-cycle Struct. Eng. (PLSE 2015), 459-465. https://doi.org/10.14264/uql.2016.1117.

Alam, M.I., Fawzia, S., Zhao, X.L.M., and Remennikov, A. (2020). "Numerical modeling and performance assessment of frp-strengthened full-scale circular-hollow-section steel columns subjected to vehicle collisions". J. Compos. Constr., 24, 1-18. https://doi.org/10.1061/(ASCE)CC.1943-5614.00010 11.

Zhang, X., and Hao, H. (2019). "Improved impact-resistant capacity of segmental column with fibre-reinforced polymer wrap". Int. J. Impact Eng., 125, 117-133. https://doi.org/10.1016/j.ijimpeng.2018.11.009.

Zhang, X., Hao, H., and Li, C. (2016). "Experimental investigation of the response of precast segmental columns subjected to impact loading". Int. J. Impact Eng., 95, 105-124. https://doi.org/10.1016/j.ijimpeng.2016.05.005.

Sharma, H., Gardoni, P., and Hurlebaus, S. (2014). "Probabilistic demand model and performance-based fragility estimates for RC column subject to vehicle collision". Eng. Struct., 74, 86-95. https://doi.org/10.1016/j.engstruct.2014.05.017.

Abdel-Nasser, Y., Elhewy, A.M.H., and Al-Mallah, I. (2017). "Impact analysis of composite laminate using finite element method". Ships Offshore Struct., 12, 219-226. https://doi.org/10.1080/17445302.2015.1131005.

Mokhatar, S.N., and Abdullah, R. (2012). "Computational analysis of reinforced concrete slabs subjected to impact loads". Int. J. Integr. Eng., 4, 70-76.

Kadhim, M.M.A., and Adheem, A.H. (2018). "Numerical modeling of CFRP-strengthened reinforced concrete beams under impact loading". J. Eng. Sustain. Dev., 22, 97-105.

El-Tawil, S., Severino E., and Fonseca, P. (2003). "Collision of vehicles with bridge piers". J. Bridge Eng., 10, 637-640. https://doi.org/10.1016/B978-008044046-0. 50156-1.

Hadi, M.N.S., and Widiarsa, I.B.R. (2012). "Axial and flexural performance of square RC columns wrapped with CFRP under eccentric loading". J. Compos. Constr., 16, 640-649. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000301.

Alam, M.I., Fawzia, S., and Zhao, X.L. (2016). "Numerical investigation of CFRP-strengthened full-scale CFST columns subjected to vehicular impact". Eng. Struct., 126, 292-310. https://doi.org/10.1016/j.engstruct.2016.07.058.

Niza, M.S. (2012). “Computational analysis of reinforced concrete slabs subjected to impact loads”. International Journal of Integrated Engineering, 4 (2).

Do, T.V., Pham, T.M., and Hao, H. (2018). “Numerical investigation of the behavior of precast concrete segmental columns subjected to vehicle collision”. Engineering Structures, 156, 375-393.

Kiran, K.K., and Noroozinejad Farsangi, E. (2021). "Blast demand estimation of RC moment-resisting frames using a proposed multi-modal adaptive pushover analysis procedure". International Journal of Engineering, 34 (1), 46-55.

Minh, H.L., Khatir, S., Wahab, M.A., and Cuong-Le, T. (2021). "A concrete damage plasticity model for predicting the effects of compressive high-strength concrete under static and dynamic loads". Journal of Building Engineering, 44, 103239.

Sha, Y., and Hao, H. (2015). "Laboratory tests and numerical simulations of CFRP-strengthened RC pier subjected to barge impact load". International Journal of Structural Stability and Dynamics, 15 (02), 1450037.

Takla, M., and Tarsha, I. (2020). "Effect of temperature on carrying capacity of concrete columns confined with multi-layers of CFRP". Jordan Journal of Civil Engineering, 14 (1).