3rd Conference on Sustainability in Civil Engineering (CSCE'21)
Department of Civil Engineering
Capital University of Science and Technology, Islamabad Pakistan

# Analytical Investigation of Typical Scale Down Bridge Pier Retrofitted with CFRP under Seismic Loading

[a]Mustahsan Iqbal, [b]Muhammad Khalid Hafiz, [c]Dr. Qaiser-uz-Zaman Khan

a: Civil Engg. Department, University of Engineering & Technology Taxila, Pakistan, mustahsaniqbal3@gmail.com
b: Civil Engg. Department, University of Engineering & Technology Taxila, Pakistan, raokhalidhafeez@gmail.com
c: Civil Engg. Department, University of Engineering & Technology Taxila, Pakistan, dr.qaiser@uettaxila.edu.pk

***Abstract:*** An earthquake measuring magnitude Mw 7.6 struck the Pakistan-administered part of Kashmir on 8 October 2005.As a result, many bridges experienced earthquake-associated damage of varying degree. It was essential to improve their strength and soundness. One of the modern techniques of Rehabilitating structure includes Retrofitting of bridge pier with Fiber Reinforced Polymers (FRP). This confines the concrete and cause a considerable improvement in strength of column. In order to investigate the effectiveness of Carbon Fiber Reinforced Polymers (CFRP), simulation of scaled down (1:4) High Strength Concrete (HSC) circular bridge pier models was carried out in current research using state of the art engineering simulation software "Seismostruct". The model was subjected to Quasi-Static Cyclic Tests (QSCT) and Pushover Analysis to determine improvement of strength, ductility and other dynamic properties. A load mass of 42.4 kips (19.24 tf) was added at top of model as gravity load. The model was retrofitted with CFRP wraps and analyzed till failures at their potential plastic zones. The purpose of this simulation was to evaluate seismic response of Bridge piers. The results showed that retrofitting of R.C columns with CFRP improves their strength and renders them capable to dissipate more energy.

***Key Words:*** CFRP, High strength concrete, Quasi static cyclic Tests, Pushover Analysis, Retrofitting.

## 1. INTRODUCTION

Earthquake can be deadliest forces of nature that can shake the structures to their limits. Whenever an Earthquake occurs Bridges are more vulnerable to damage and if they get damaged whole system of transportation gets ceased. Usually, after any major catastrophe, the codes are revised in order to meet new challenges. So after the earthquake of 2005 in Pakistan, there was a dire need to revise the seismic zone as a result of which a new Building Code of Pakistan (2007) was formed known as BCP-2007. This new building code upgrades the zones of almost every city of Pakistan putting them into higher seismic prone zone. Many bridges were constructed before October 2005 and those were in accordance with the West Pakistan Highway Code (1967). Therefore, bridges were susceptible to damage and needed retrofitting to enhance their strength and ductility demands.

The availability of various inelastic element modeling in FEA programs have strengthen analytical techniques. A simple analytical procedure was proposed recently and is based on the ratio between displacement capacity of a structure corresponding to several limit states and displacement demand for an earthquake event as obtained from the corresponding displacement spectrum[1]. In another research, Reinforced concrete column were tested under cyclic loading. Based on results, following conclusion were made (i) The fiber element analysis which is based on cyclic constitutive models of longitudinal reinforcement and concrete confined by both CFS and ties provides good numerical simulation of experimental results (ii) The hysteric response of as-built columns can be increased by CFS jacketing which is effective at increasing lateral confinement, allowing increase in strength and ductile behavior[2]. A research study was carried out in which columns were continuously reinforced by CFRP and were tested under constant compression load combined with a horizontal quasi static cyclic load test. The results concluded that CFRP confinement completely changed the failure mode of the columns[3]. An extensive research was made on efficient rehabilitation techniques for structures damaged after historic earthquake of 2008. An experimental investigation was carried out to study the effect of retrofitting on change in dynamic properties of scale down bridge piers. Piers were tested twice, first in damaged state, then retrofitted with single layer of CFRP. Results showed that energy dissipation and ductility of retrofitted column increases as compared to control model [4].A low strength scale down concrete bridge pier model was simulated and analyzed using analytical techniques. Results show that retrofitting of undamaged state improves their ductility and made them capable to dissipate the energy more efficiently [5]. In another study, externally bonded Carbon Fiber Reinforced Polymer (CFRP) retrofit technique was implemented to improve the behavior of RC columns tested under constant axial load and cyclic lateral load. It was found that (i) CFRP retrofitting in the lateral direction at the plastic hinge region improved deformation capacity of the plastic hinge region tested under cyclic lateral load (ii) With CFRP lateral confinement, behavior of slender RC columns tested under low and moderate axial load was improved in terms of ductility, energy dissipation and failure mechanism (iii) Using longitudinal CFRP retrofitting with the lateral CFRP confinement increased both the effective stiffness and the lateral strength of the column [6]. An investigation was carried out in which plastic hinge region of FRP-confined RC Columns was studied by finite element model. The results of investigation were (i) The plastic hinge length of FRP-confined columns is very different from that of normal RC Column. Lengths of both the rebar yielding zone and curvature localization zone increases first and then decrease as the confinement ratio increases (ii) For flexural retrofitting of the RC Columns, FRP jacket needs to cover at least the length of concrete crushing zone, which is significantly affected by FRP confinement[7]. In past bridges, which were built according to specifications of old design codes do not perform well during seismic events and are considered as, insufficient in strength and ductility requirement, which in turn demands retrofitting to improve their strength and ductility. The subject research deals with the numerical evaluation and simulation of High Strength Concrete Bridge Pier retrofitted with Carbon Fiber Reinforced Polymer (CFRP) to find out its effectiveness in increasing the strength of pier.

In this research, simulation and analytical investigation of experimental research work, is carried out by using state of the art finite element software "Seismostruct". In experimental work, Quasi-Static test is performed on 1:4 scale down Bridge Pier Model having high strength of 6192 psi. The piers were first tested in their undamaged state and in next phase rehabilitation of damaged column were carried out, wrapping the damage column with carbon fiber reinforced polymer (CFRP). The pier columns after rehabilitation were again subjected to same testing and a comparison was presented in various dynamic properties of both states (Undamaged state and strengthen with CFRP state).In the current research finite element software like Siesmostruct was used to stimulate the behavior of bridge piers under seismic events. A comparison of test results of simulated model was made with experimental results of High Strength Concrete test and also with test results of low strength concrete (1800 psi and 2400 psi) model.

## 2. Methodology of Work:

The current research incorporates the finite element modeling of High Strength bridge pier column for assessment of their dynamic properties. The hysteretic performance and the energy dissipation capacity was assessed for the columns wrapped with CFRP Layers. The effectiveness of CFRP was estimated with high strength circular columns on term of increase in lateral load capacity. The model geometry, different dimensions, type and magnitude of applied loading are same as done through experimental work. Firstly the control specimen was modeled and analyzed through Finite Element Method (FEM) by using "Seismostruct". Then the model was retrofitted by wrapping it with layers of Carbon Fiber Reinforced Polymer (CFRP) and analyzed again using the same program. Model was retrofitted with CFRP before damaging, suggesting that the methodology adopted is pre-retrofitted.

First of all, bridge pier was scale down to 1:4 to its original dimensions. The height of pier obtained after scaling down was 6 ft and 3 in (75 in) with 1 ft (12 in) diameter. A total of 16#3 longitudinal steels bars were provided in the pier with lateral reinforcement of #1@6 in c/c spacing. Concrete cover was kept at 1.25 in. Afterwards, the same is simulated in Seismostruct for assessing the effectiveness and performance of confined concrete. A 3D solid model of bridge pier was simulated in version 2020 of Seismostruct. Element type of pier is inelastic force-based (FB) frame element. The pier has been integrated into 5 sections and is being represented by 400 fibers. Concrete used has mean compressive strength 6.192 ksi, mean tensile strength 0.382 ksi, modulus of elasticity 4453.95 ksi. Steel used has yield strength 83 ksi, modulus of elasticity 29000 ksi for longitudinal reinforcement and has mean strength value of 19.5ksi for spiral reinforcement. CFRP used have fiber thickness of 0.04 in, tensile strength 153 ksi, tensile modulus 9400 ksi. Among various sort of analysis facilities available in the software static pushover analysis was utilized to stimulate Quasi Static Cyclic Load. In addition to the lateral load, the column was subjected to gravity load of 42.2 kips in the form of concrete blocks placed at the top of column.

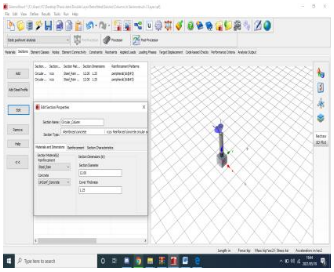

*Figure 1: Numerical Modeling*

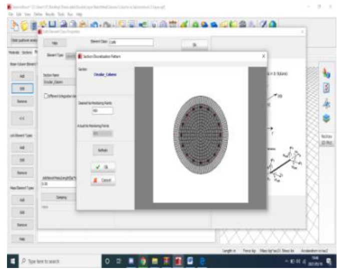

*Figure 2: Meshing(Integrated into 5 sections and 400 fibers)*

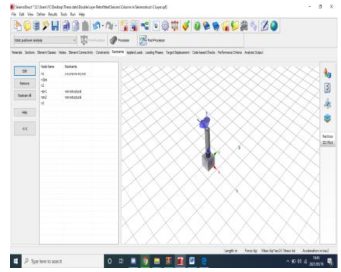

*Figure 3: Boundary Conditions (Fixed at bottom)*

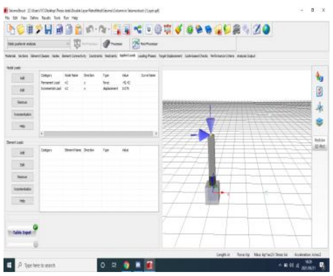

*Figure 4: 3D View (Showing vertical and lateral load)*

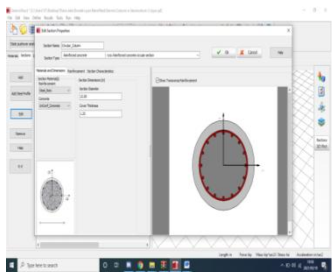

*Figure 5: Cross-Section (16#3 bars, 1in diameter, 1.25in cover)*

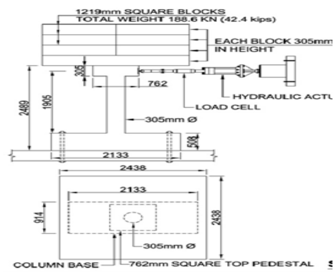


*Figure 6: Plan and Elevation ( 6ft-3in)*

The lateral load simulated on the circular column is applied in the terms of different drift levels in one particular direction and after that a restoring force in the opposite direction thus forming the hysteresis loop for each cycle. The point of application of lateral force is 75in (1905 mm) from base. Drift levels applied are 0.1%, 0.25%, 0.5%,1%.2%,3%,4%,5% of height of pier. Displacements are calculated against these drift levels like 0.1% of 1905mm is 1.9mm upto 5%. Data related to various drift level and corresponding number of cycles executed in research work are given in the Table 1.

***Table 1: Different Drift Level and No. of Cycle Executed***

| Percentage Drift (%) | 0.1 | 0.25 | 0.5 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| No. of Cycle for each Drift level | Two | Two | Two | Two | Two | Two | Two | Two |
| Displacement (mm) | 1.9 | 4.8 | 9.6 | 19.2 | 38.4 | 57.6 | 76.8 | 96 |

## 3. Seismostruct Results:

Simulation of Quasi-Static Cyclic Load tests was carried out at different drift levels. Subsequent to simulating the Quasi-Static Cyclic Load Testing, the accompanying actions were taken:

a) The output data obtained after analysis of model from Seismostruct was rearranged in manageable format and transferred to spreadsheets of excel program.
b) Hysteresis loop curve at various drift level (in) against lateral load (kip) were plotted individually in excel program. The hysteresis curves for Control Model (CM), Undamaged Retrofitted Models-Single Layer (UDRM-SL) and Undamaged Retrofitted Model- Double Layer (UDRM-DL) for High Strength columns of 6192 psi have been shown from Figure 7 to Figure 9. The following information was derived from these curves:
    i. Area under each curve gives the value of energy dissipation at different drift level.
    ii. Maximum lateral load sustained by the column at each drift level shows the strength of the pier column at different drift level.
c) Once the maximum lateral load was determined for the respective drift levels, graphs were plotted for peak lateral loads against different drift value, named as backbone curve from figure 10 to figure 12.

It was observed that energy dissipation keeps on increasing with the increase in drift level. Also it is worth noticing that before 1% drift level that energy dissipation was negligible which shows that there was very less or no energy dissipation. These backbone curves of Control Model (CM), Undamaged Retrofitted Model- Single Layer (UDRM-SL) and Undamaged Retrofitted Model- Double Layer (UDRM-DL) of High Strength Concrete Bridge

Pier (6192 psi) were then compare with backbone curves of Control Model (CM), Undamaged Retrofitted Model- Single Layer (UDRM-SL) and Undamaged Retrofitted Model- Double Layer (UDRM-DL) of Low Strength Concrete Bridge Pier Columns (1800 psi and 2400 psi) are shown in Figure 10 to Figure 15.

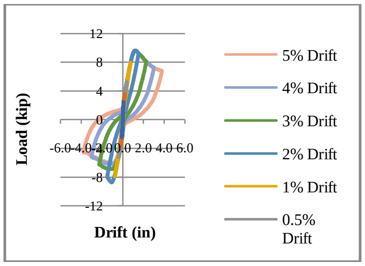


*Figure 7: Hysteresis Curve of Control Models (6192 psi)*

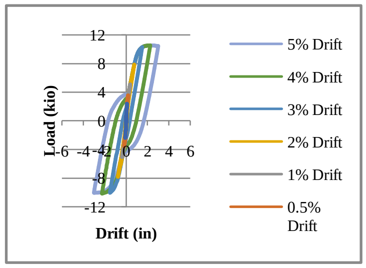


*Figure 8: Hysteresis Curve of Single Layer Models (6192 psi)*

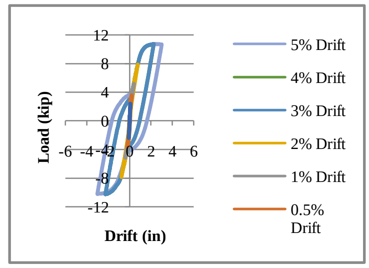


*Figure 9: Hysteresis Curve of Double Layer Models (6192 psi)*

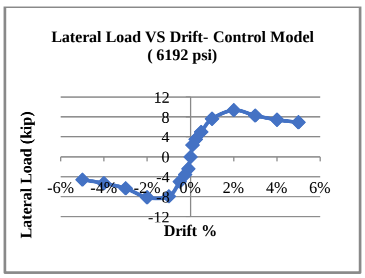


*Figure 10: Backbone Curve- Control Models*

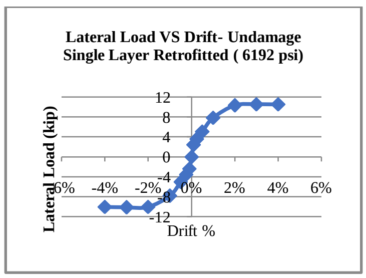


*Figure 11: Backbone Curve-Single Layer Retrofitted Models*

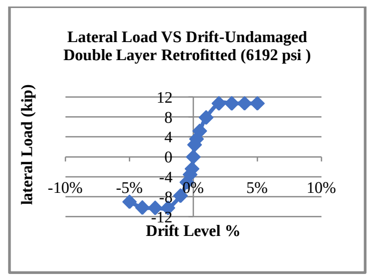


*Figure 12: Backbone Curve - Double Layer Retrofitted Models*

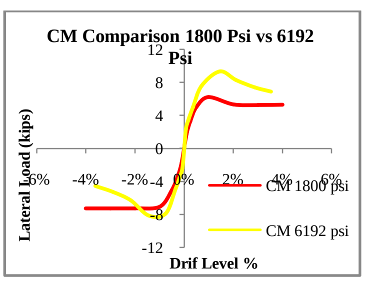


*Figure 13: CM- Lateral Load VS Drift (1800 psi vs 6192 psi)*

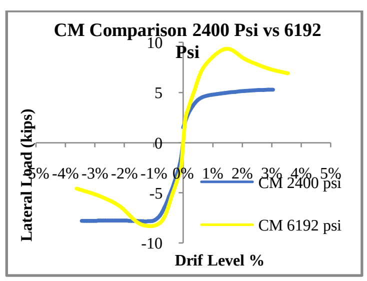


*Figure 14: CM-Lateral Load VS Drift (2400 psi vs 6192psi)*

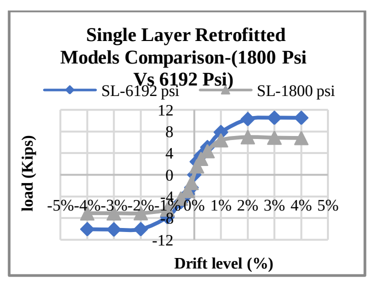


*Figure 15: UDRM-SL- Lateral Load VS Drift (1800 psi vs 6192psi)*

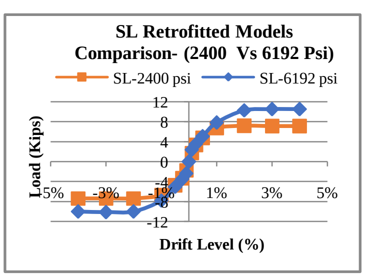


*Figure 16: UDRM-SL Comparison- Lateral Load VS Drift (2400 Psi VS 6192 psi)*

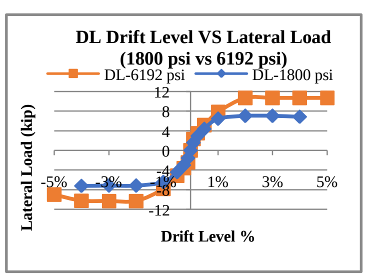


*Figure 17: UDRM-DL Comparison- Lateral Load VS Drift (1800 Psi VS 6192 psi)*

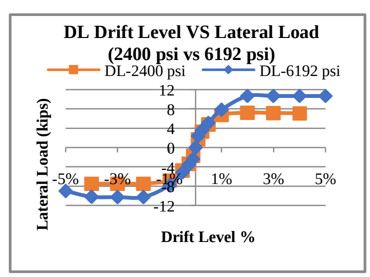


*Figure 18: UDRM-DL Comparison- Lateral Load VS Drift (2400 Psi VS 6192 psi)*

## 4. Discussion on Results:

Pier models were analyzed in their control state and undamaged retrofitted state. Quasi static cyclic loading was applied on each model at different drift levels. Graphs were drawn from the data which was obtained as a result of application of these drifts. These graphs depict the load carried/energy dissipated by the model and are known as hysteresis loop curves. The peak values of these curves were calculated both from positive and negative sides, and plotted which as a result gives the backbone curves. It was observed that energy dissipation goes on increasing with the increase in drift level and also pier is capable to dissipate significantly large amount of energy when retrofitted with CFRP as compare to control state. It was also worth noting that as number of layers of CFRP increases, energy dissipation also increases. Concrete strength also plays a key role. Energy dissipation in case of High Strength Concrete (HSC) is very huge as compare to energy dissipated in case of Low Strength Concrete (LSC). A comparison was done between backbone curves for Control Models (CM), Undamaged Retrofitted Models- Single Layer (UDRM-SL), Undamaged Retrofitted Models- Double Layer (UDRM-DL) of High strength concrete (6192 psi) and Control Model (CM), Undamaged Retrofitted Models- Single Layer (UDRM-SL) and Undamaged Retrofitted Models- Double Layer (UDRM-DL) of Low Strength Concrete (1800 psi and 2400 psi).

Following are the results of comparisons:

*Table 2: Single Layered CFRP Model Results - Percentage Increase in Load carrying Capacity (1800 vs 2400 vs 6192 psi)*

| SINGLE LAYERED MODELS RESULTS | | | | | | |
|---|---|---|---|---|---|---|
| **COMPARISON BETWEEN CONTROL AND UNDAMAGED MODELS OF HSC 6192 Psi** | | | | | | |
| **Model Type** | **Model Nomenclature** | **Max Lateral Force (Kips) North Direction** | **Max Lateral Force (Kips) South Direction** | **Average Lateral Force (Kips)** | **Percentage Increase** |
| **Undamaged Models** | CM-6192 psi | 9.63 | 8.13 | 8.88 | |
| | UDRM-SL 6192 psi | 10.5282 | 10.1305 | 10.32935 | 16.32% |
| | CM-6192 psi | 9.63 | 8.13 | 8.88 | |
| | UDRM-DL 6192 psi | 10.714 | 10.25 | 10.482 | 18.04% |
| COMPARISON BETWEEN CONTROL MODELS OF HSC 6192 Psi & LSC 1800 & 2400 Psi | | | | | |
| **Model Type** | **Model Nomenclature** | **Max Lateral Force (Kips) North Direction** | **Max Lateral Force (Kips) South Direction** | **Average Lateral Force (Kips)** | **Percentage Increase** |
| **Control Models** | CM-1800 Psi | 6.23 | 7.25 | 6.74 | |
| | CM-6192 Psi | 9.63 | 8.13 | 8.88 | 31.75% |
| | CM - 2400 Psi | 5.28 | 7.85 | 6.565 | |
| | CM-6192 Psi | 9.63 | 8.13 | 8.88 | 35.26% |
| COMPARISON B/W UNDAMAGED RETROFITTED MODELS - SINGLE LAYER CFRP OF HSC 6192 Psi & LSC 1800 & 2400 Psi | | | | | |
| **Model Type** | **Model Nomenclature** | **Max Lateral Force (Kips) North Direction** | **Max Lateral Force (Kips) South Direction** | **Average Lateral Force (Kips)** | **Percentage Increase** |
| **UDRM-SL** | UDRM-SL 1800 Psi | 6.95 | 7.09 | 7.02 | |
| | UDRM-SL 6192 Psi | 10.5282 | 10.31 | 10.4191 | 48.42% |
| | UDRM-SL 2400 Psi | 7.19 | 7.36 | 7.275 | |
| | UDRM-SL 6192 Psi | 10.5282 | 10.31 | 10.4191 | 43.22% |

*Table 3: Double Layered CFRP Model Results - Percentage Increase in Load carrying Capacity (1800 vs 2400 vs 6192 psi)*

| DOUBLE LAYER MODELS RESULTS | | | | | |
|---|---|---|---|---|---|
| COMPARISON B/W UNDAMAGED RETROFITTED MODELS - DOUBLE LAYER CFRP OF HSC 6192 Psi & LSC 1800 & 2400 Psi | | | | | |
| **Model Type** | **Model Nomenclature** | **Max Lateral Force (Kips) North Direction** | **Max Lateral Force (Kips) South Direction** | **Average Lateral Force (Kips)** | **Percentage Increase** |
| **UDRM-DL** | UDRM-DL 1800 Psi | 7.07 | 7.19 | 7.13 | |
| | UDRM-DL 6192 Psi | 10.714 | 10.25 | 10.482 | 47.01% |
| | UDRM-DL 2400 Psi | 7.19 | 7.45 | 7.32 | |
| | UDRM-DL 6192 Psi | 10.714 | 10.25 | 10.482 | 43.20% |

## 5. Conclusions:

After the detailed analysis of results, it was found out that:

- After comparing Control Models of Low Strength Concrete (1800 & 2400 Psi) and Control Model of High Strength Concrete Models (6192 Psi), it was found that Load carrying Capacity was increased by **31.75%** for **1800 Psi vs 6192 Psi** and **35.26%** for **2400 Psi vs 6192 Psi** in case of **Control Models**.
- After comparing Undamaged Single Layered CFRP Wrapped Low Strength Concrete models (UDRM-SL) of 1800 & 2400 Psi and Undamaged Single Layered CFRP Wrapped High Strength Concrete Models (UDRM- SL 6192 Psi) , it was found that the Load carrying Capacity was **increased** by **48.42%** for **1800 Psi vs 6192 Psi** and **43.22%** for **2400 Psi vs 6192 Psi**.
- After comparing Undamaged Double Layered CFRP Wrapped Low Strength Concrete models (UDRM-DL) of 1800 & 2400 Psi and Undamaged Double Layered CFRP Wrapped High Strength Concrete Models (UDRM-DL 6192 Psi), it was found that the Load Carrying Capacity was **increased** by **47.01%** for **1800 Psi vs 6192 Psi** and **43.20%** for **2400 Psi vs 6192 Psi**.

This clearly shows that Load Carrying capacity is increased by increasing strength of Concrete as well as wrapping of a layer of CFRP. The difference between finite element model results and experimental results depends upon factors like human error, instrumental error and realistic environmental conditions.

## Acknowledgement:

The author would like to thanks Engr. Hafiz Zain Saeed and Engr. Amir Jamshed who helped throughout the research work, particularly Earthquake Engineering staff of CED department of UET Taxila. The careful review and constructive suggestions by anonymous reviewers are gratefully acknowledged.

## References:

[1] Calvi∗ , G.M., A DISPLACEMENT-BASED APPROACH FOR VULNERABILITY EVALUATION OF CLASSES OF BUILDINGS. Journal of Earthquake Engineering, 1999. 3(3): p. 411-438.

[2] Zafra, R. and K. Kawashima, ANALYSIS OF CARBON FIBER SHEET RETROFITTED RC BRIDGE COLUMNS. 2008.

[3] Colomb, F., et al., Seismic retrofit of reinforced concrete short columns by CFRP materials. Composite Structures, 2008. 82: p. 475-487.

[4] Khan, Q.-U.-Z., et al., Seismic Evaluation of Repaired and Retrofitted Circular Bridge Piers of Low-Strength Concrete. Arabian Journal for Science and Engineering, 2015. 40(11): p. 3057-3066.

[5] Saeed, H.Z., et al., Experimental and finite element investigation of strengthened LSC bridge piers under Quasi-Static Cyclic Load Test. Composite Structures, 2015. 131: p. 556-564.

[6] Aules, W., Behavior of Non-Ductile Slender Reinforced Concrete Columns Retrofit by CFRP Under Cyclic Loading. 2019.

[7] Yuan, F., Y.-F. Wu, and C.-Q. Li, Modelling plastic hinge of FRP-confined RC columns. Engineering Structures, 2016. 131.