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Investigation of High Strength Concrete Bridge Piers Retrofitted with CFRP under Seismic Loading

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Abstract: One of the most challenging natural calamities under the umbrella of Civil Engineering, which may damage the structures and life as well is Earthquake. On 8th October 2005, a similar type of catastrophe was faced significantly in the Northern areas of Pakistan. Many Bridges got damaged due to this but some remained unaffected in various regions. It is essential to improve their strength and soundness which can be achieved with the help of Retrofitting with FRPs (Fiber Reinforced Polymers). Now a days, High strength concrete (HSC) is being employed in Bridge construction. This research targets the behavior of HSC before and after retrofitting. An experimental study was performed by applying Quasi static cyclic loadings (QSCT) with axial load applied on scaled down (1:4) RC bridge piers under different drift levels. The scaled down pier models were retrofitted with carbon fiber reinforced polymer (CFRP) sheets. The specimens were tested under QSCT against various drift levels ranging from 0 to 5%. Hysteresis loops are generated against each category of drift level which shows the lateral load carrying capacity of the Bridge pier against that specific Drift level. Results show that load carrying capacity of retrofitted bridge piers was enhanced due to the external confinement by CFRP sheets due to which the vulnerability/failure zones of structures were also upgraded. The amount of lateral load carried by the retrofitted model was more than the original or un-retrofitted model. The bridges made of HSC after the revision of building code need structural assessment and their load carrying capacity can be increased after retrofitting with single or double layer of CFRP and be brought within the safety limits as per new building code requirements. In the light of results of this research, it is considered that these bridges after retrofitting will become capable of resisting considerably more loads as per requirements of the new Building Code.

Key Words: CFRP, Energy dissipation, High strength concrete, Quasi static cyclic Loading, Retrofitting.

1 INTRODUCTION

Bridges serve as the jugular vein of the transportation system/network. Whenever an Earthquake or any other calamity occurs, Bridges are most susceptible to damage which as a result may halt the whole transportation network of the specific area. Mostly, Bridges built in Pakistan have not been structurally designed as per present seismic necessities. After the incident of 8th October 2005 in Pakistan, seismic danger maps and seismic zoning has been modified shaping a piece of the new Building Code of Pakistan (2007) known BCP-2207. But many Bridges were constructed before October 2005 and those were in accordance with the West Pakistan Highway Code (1967). An investigation was carried out for the seismic behavior of Reinforced concrete (RC) Piers wrapped with fiber reinforced plastic (FRP) composites straps. Results concluded that RC piers depicted notable improvements in strength and translational ductility [1]. Another study highlighted Short Columns investigation after wrapping with FRP composite tubes. Results indicated that wrapping was effective in enhancing the ductility, strength and energy dissipation capacity of tested concrete columns [2]. In another research, Surface mounted FRP rods were affixed in the footings and evaluated the flexural capacity of Rectangular Bridge Piers. It was found that the Flexural capacity of the Piers was increased [3]. Four low strength concrete (LSC) pier column models (1800 & 2400 Psi) scaled at 1:4 were subjected to QSCT. It was concluded that energy dissipation capacity of 1800 & 2,400 columns is almost same. Thus strength of concrete in this range does not affect the total energy absorption [4].

The columns which were damaged during the experimentation under reference[4] were retrofitted and also additional models were casted and retrofitted in undamaged state to investigate the effect of retrofitting on Load carrying capacity and Energy Dissipation of LSC (1800 Psi & 2400 Psi) RC piers. Comparison indicated that load carrying capacity of Damaged but retrofitted models was enhanced along with their strength and ductility to withstand even larger potential earthquakes [5]. A study was conducted on strengthening RC columns with a longitudinal CFRP sheet anchored to the column base. Results concluded that the use of a CFRP sheet with a CFRP anchor improved both the effective stiffness and the lateral strength of the RC columns [6]. The behavior of Non- Ductile slender reinforced concrete columns retrofitted with CFRP subjected to cyclic loading revealed significant improvement in terms of displacement ductility, load level, energy dissipation and failure mechanism [7]. Experimental work was conducted to evaluate the effectiveness of application of CFRP sheets to retrofit beams columns non-ductile joints. The load carrying capacity and number of cycles were increased. Applying two layers of CFRP sheets seemed less effective than one layer [8].

In the past, the bridges and components were constructed using High strength Concrete as per the criteria of the previous (obsolete) Building Code. But now after the revision of the Building Code and introduction of new Seismic zoning, there is a dire need to strengthen the existing bridge piers in order to withstand further events of severe earthquakes. The present research basically aims to review and reckon the lateral load carrying capacity of High strength concrete (HSC) bridge piers after these are retrofitted with CFRP. Also, the research highlights that what will be the behavior of CFRP retrofitted piers which got damaged as a result of any Earthquake event. This research also includes the comparison of performance of Bridge piers made of Low strength concrete (1800 and 2400 Psi) and High Strength concrete (6192 Psi) in terms of load carrying capacity. Research study on Low strength concrete has already been carried out vide references [4] and [5]. The test results of both these researches are obtained for comparison purposes with the test results of the present research. The results clearly depict a significant increase in load carrying capacity in HSC models the details of which are mentioned in section 3 of this research.

2 Experimental Setup

The test was conducted in the Earthquake Engineering Center (EEC) of Department of Civil Engineering UET Peshawar as adequate facilities and required equipment was available there. The Following tests were staged on the specimens:

i) Quasi-Static Cyclic loading tests (QSCT)   ii) Compressive strength tests (Concrete Cylinder tests)

The research comprises of QSC testing of Six (6) bridge pier models with the following properties:

- The pier models are scaled down to 1:4 scale with the help of similitude analysis having concrete strength of 6.192 ksi. The complete experimental setup with all the geometric details can be visualized in Figure 1. CFRP HEX 103-C is used for retrofitting with a fabric thickness of 1.016 mm, tensile strength of 153 ksi and tensile modulus of 9400 ksi. The steel used possesses yield strength of 83 ksi with modulus of elasticity 29000 ksi. The whole pier model assembly is loaded with a physical load of 42.4 kips. The models which are subjected to QSCT include two models in each of the category i-e. Control Models (CM), Damaged retrofitted columns (DRM) and Undamaged retrofitted columns (UDRM).

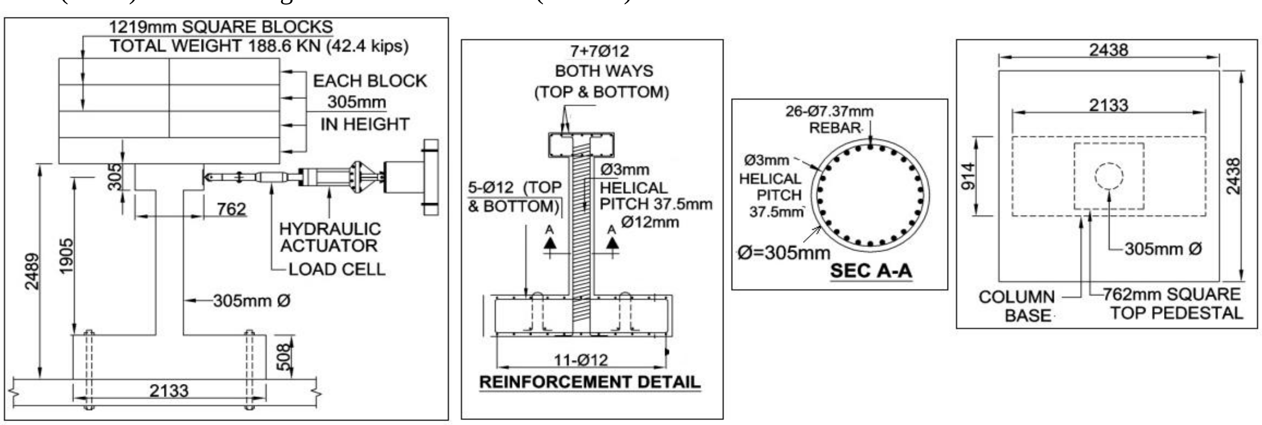

Figure 1. Experimental setup depicting all the geometric details, reinforcement details as well as loading details.

In order to predict the effects of improvements due to retrofitting on scaled down models, the model testing was carried out as per the following schedule:

a. Two test models of high strength concrete (6192 psi) were casted and both were subjected to Quasi static cyclic loading tests (QSCT) without any retrofitting and were tested up to failure. These models are referred in the research as Control Models or CM.

b. These two damaged models were repaired which constituted filling and repairing of cracks and retrofitted with CFRP. One model was retrofitted with single layer of CFRP which is referred as Damaged Retrofitted Model – Single Layer (DRM-SL), whereas the other model was retrofitted with double layer of CFRP which is referred as Damaged Retrofitted Model – Double Layer (DRM-DL). These two repaired and retrofitted models were subjected to QSCT up to failure. The tests were studied for evaluation of load carrying capacity, ductility, strength and energy dissipation of the models.
c. Two additional models of similar high strength concrete (6192 psi) were prepared and retrofitted in their original/Undamaged state and then subjected to QSCT. One model was retrofitted with single layer of CFRP which is referred as Undamaged Retrofitted Model – Single Layer (UDRM-SL), whereas the other model was retrofitted with double layer of CFRP which is referred as Undamaged Retrofitted Model – Double Layer (UDRM-DL).
d. High Strength Concrete (6192 psi) Cylinders were prepared and tested for their compressive strength.
e. QSCT were performed at different drift levels i.e. 0 to 4% and 5% in some cases. The reason that 5% drift is involved in few cases depended either upon the failure criteria set for the models or due to safety concerns as the huge physical loading of 42.4 Kips was placed over the damaged column models of one feet diameter only and was subjected to repeated reverse cyclic loading. This was a potential threat to the laboratory equipment as well as to the staff working in the laboratory. After QSCT on all the damaged models, the sequence of action was as following:
   - The data recorded on the data logger was rearranged in the format that could be managed in the spread sheets of IGOR Pro.
   - Hystereses curves were formed for each drift level separately which are attached below in Figure 1, 2 & 3. The cyclic loading of QSCT for lateral load with the change in drift levels has provided hysteresis curves for all the models. With the help of these hysteresis curves, Backbone curves are generated which give the maximum load carried by a pier under a certain drift level.

Figure 2. Test assembly setup with physical loading of 42.4 Kips.

Figure 3. Damaged Column, Cracks & Spalling of concrete.

Figure 4.Outer repair works with cementitious mix after filling of cracks.

Figure 5. Grinded and Prepared surface of pier for CFRP application.

Figure 6. Application of CFRP (HEX-103-C) to pier.

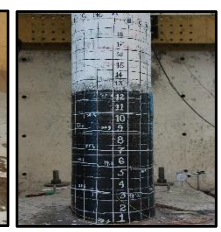

Figure 7. Final shape of pier after application of CFRP.

3 Discussion on Experimental Results:

The data obtained from the experimental results by the data logger was analyzed by using a software named IGOR Pro in which data as arranged in the form of sheets. A total of 6 Pier models were tested. Every model was subjected to QSCL at various drift levels ranging from 0 to 5%.

These graphs depict the load carried/resisted by the model. When these graphs are combined, they form a hysteresis curve as shown in Figure 1, 2 & 3. The peak values of these curves were calculated and backbone curves were made from these values. The backbone curves for Control Models, Damaged Retrofitted Models and Undamaged Retrofitted Models of Low strength concrete (1800 psi and 2400 psi) obtained from doctoral research of Ali S. M. (2009) and M. Iqbal (2012) under reference [4] and [5] were compared with corresponding models of High Strength Concrete i-e. 6192 psi.

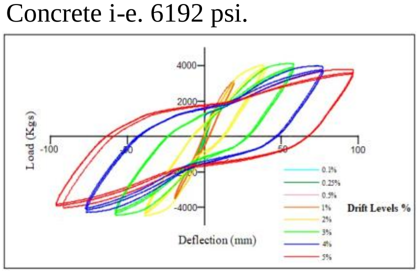

Figure 8. Hysteresis Curves – CM 6192 psi Pier Column subjected to different drift levels.

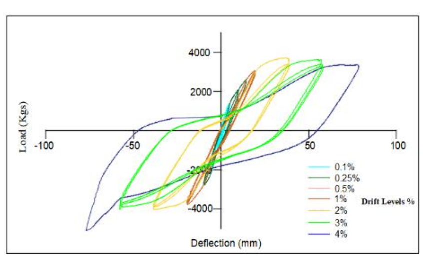

Figure 9. Hysteresis Curves - DRM 6192 psi Pier Column subjected to different drift levels.

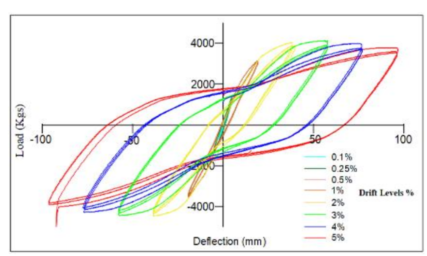

Figure 10. Hysteresis Curves - UDRM 6192 psi Pier Column subjected to different drift levels.

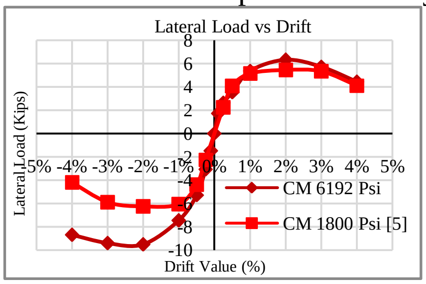

Figure 11. Control Models (CM) Backbone Curves Comparison (1800 Psi [5] vs 6192 Psi)

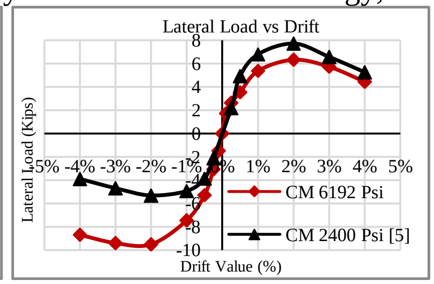

Figure 12. Control Models (CM) Backbone Curves Comparison (2400 Psi [5] vs 6192 Psi)

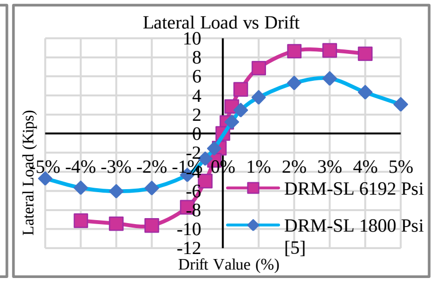

Figure 13. Damaged Retrofitted Models – Single Layer CFRP (DRM-SL) Backbone Curves Comparison (1800 Psi [5] vs 6192 Psi)

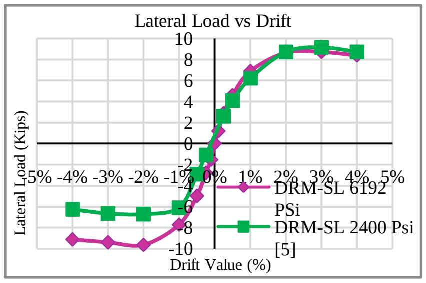

Figure 14. Damaged Retrofitted Models – Single Layer CFRP (DRM-SL) Backbone Curves Comparison (2400 Psi [5] vs 6192 Psi)

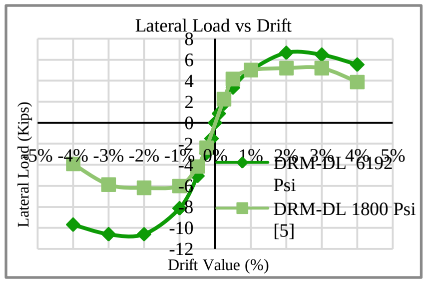

Figure 15. Damaged Retrofitted Models – Double Layer CFRP (DRM-DL) Backbone Curves Comparison (1800 Psi [5] vs 6192 Psi)

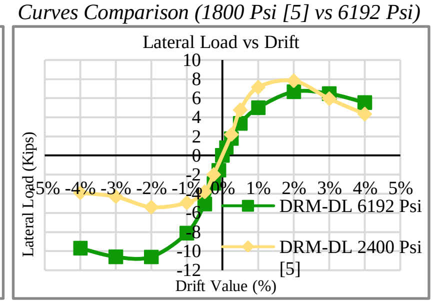

Figure 16. Damaged Retrofitted Models – Double Layer CFRP (DRM-DL) Backbone Curves Comparison (2400 Psi [5] vs 6192 Psi)

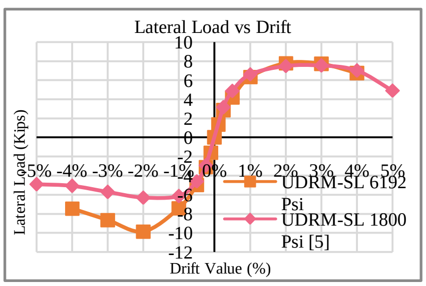

Figure 17. Undamaged Retrofitted Model-Single Layered CFRP (UDRM-SL) Backbone Curves Comparison (1800 Psi [5] vs 6192 Psi)

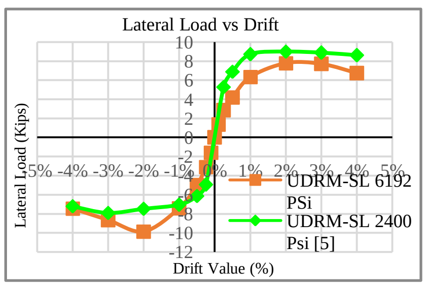

Figure 18. Undamaged Retrofitted Model-Single Layer CFRP (UDRM-SL) Backbone Curves Comparison (2400 Psi [5] vs 6192 Psi)

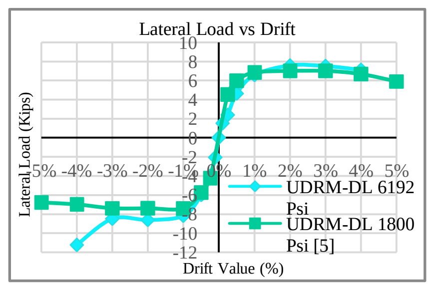

Figure 19. Undamaged Retrofitted Model-Double Layer CFRP (UDRM-DL) Backbone Curves Comparison (1800 Psi [5] vs 6192 Psi)

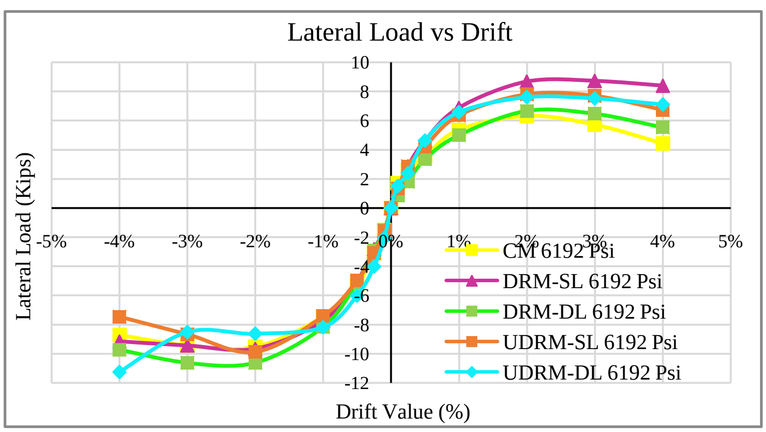

Figure 20. CM vs DRM-SL, DRM-DL, UDRM-SL &UDRM-DL (6192 psi) Self Comparison of Backbone Curves between HSC Models.

The figures above (11 to 20) represent the behavior of Load carrying capacity of Control Models (CM), Damaged retrofitted columns (DRM) and Undamaged retrofitted columns (UDRM) in a graphical comparison between the High strength concrete models (6192 psi) and Low strength concrete (1800 & 2400 psi). It is obvious from these figures that by increasing the strength of concrete, significant increases in load carrying capacity are observed.

Table 1. Single Layered CFRP Model Results - % Increase in Load carrying Capacity (1800, 2400 vs 6192 psi)

SELF COMPARISON BETWEEN HSC MODELS (SL &DL)	**COMPARISON B/W CONTROL, DAMAGED AND UNDAMAGED MODELS OF HSC 6192 Psi**					
	Model Type	**Model Nomenclature**	**Max Lat. Force (Kips) - North**	**Max Lat. Force (Kips)-South**	**Average Lateral Force (Kips)**	**Percentage Increase**
	Damaged Models	CM-6192	6.3233	9.5174	7.9204	15.96%
		DRM-SL 6192	8.7280	9.6404	9.1842	
		CM-6192	6.3233	9.5174	7.9204	9.11%
		DRM-DL 6192	6.6691	10.6142	8.6417	
	Undamaged Models	CM-6192	6.3233	9.5174	7.9204	11.51%
		UDRM-SL 6192	7.7989	9.8658	8.8323	
		CM-6192	6.3233	9.5174	7.9204	18.95%
		UDRM-DL 6192	7.5963	11.2456	9.4210	
	COMPARISON BETWEEN CONTROL MODELS OF HSC 6192 Psi & LSC 1800 & 2400 Psi					
	Model Type	**Model Nomenclature**	**Max Lat. Force (Kips) - North**	**Max Lat. Force (Kips)-South**	**Average Lateral Force (Kips)**	**Percentage Increase**
	Control Models	CM-1800 Psi	5.4400	6.2550	5.8475	35.45%
		CM-6192 Psi	6.3233	9.5174	7.9203	
SINGLE LAYERED MODELS RESULTS		CM - 2400 Psi	7.7100	5.3250	6.5175	21.52%
		CM-6192 Psi	6.3233	9.5174	7.9203	
	COMPARISON BETWEEN DRMs- SL CFRP OF HSC 6192 Psi & LSC 1800 & 2400 Psi					
	Model Type	**Model Nomenclature**	**Max Lat. Force (Kips) - North**	**Max Lateral Force (Kips) - South**	**Average Lateral Force (Kips)**	**Percentage Increase**
	DRM-SL	DRM-SL 1800 Psi	5.7745	6.0412	5.9079	55.46%
		DRM-SL 6192 Psi	8.7280	9.6404	9.1842	
		DRM-SL 2400 Psi	9.1470	6.7230	7.9350	15.74%
		DRM-SL 6192 Psi	8.7280	9.6404	9.1842	
	COMPARISON B/W UDRMs - SL CFRP OF HSC 6192 Psi & LSC 1800 & 2400 Psi					
	Model Type	**Model Nomenclature**	**Max Lat. Force (Kips) - North**	**Max Lateral Force (Kips) - South**	**Average Lateral Force (Kips)**	**Percentage Increase**
	UDRM-SL	UDRM-SL 1800 Psi	7.5399	6.3101	6.9250	27.54%
		UDRM-SL 6192 Psi	7.7989	9.8658	8.8323	
		UDRM-SL 2400 Psi	9.0000	7.9168	8.4584	4.42%
		UDRM-SL 6192 Psi	7.7989	9.8658	8.8323	

Table 2. Double Layered CFRP Model Results - Percentage Increase in Load carrying Capacity (1800 Psi vs 2400 Psi vs 6192 psi)

DOUBLE LAYERED MODELS RESULTS	**COMPARISON B/W CONTROL, DAMAGED & UNDAMAGED MODELS OF HSC 6192 Psi**					
	COMPARISON BETWEEN CMs OF HSC 6192 Psi & LSC 1800 & 2400 Psi					
	Model Type	**Model Nomenclature**	**Max Lat. Force (Kips) - North**	**Max Lateral Force (Kips) - South**	**Average Lateral Force (Kips)**	**Percentage Increase**
	Control Models	CM-1800 Psi	5.4400	6.2550	5.8475	35.45%
		CM-6192	6.3233	9.5174	7.9203	
		CM - 2400 Psi	7.7100	5.3250	6.5175	21.52%
		CM-6192	6.3233	9.5174	7.9203	
	COMPARISON BETWEEN DRMs - DL CFRP OF HSC 6192 Psi & LSC 1800 & 2400 Psi					
	Model Type	**Model Nomenclature**	**Max Lat. Force (Kips) - North**	**Max Lateral Force (Kips) - South**	**Average Lateral Force (Kips)**	**Percentage Increase**
	DRM-DL	DRM-DL 1800 Psi	5.2000	6.2000	5.7000	51.61%
		DRM-DL 6192 Psi	6.6691	10.6142	8.6417	
		DRM-DL 2400 Psi	7.8200	5.4000	6.6100	30.74%
		DRM-DL 6192 Psi	6.6691	10.6142	8.6417	
	COMPARISON BETWEEN UDRMs - SL CFRP OF HSC 6192 Psi & LSC 1800 & 2400 Psi					
	Model Type	**Model Nomenclature**	**Max Lat. Force (Kips) - North**	**Max Lateral Force (Kips) - South**	**Average Lateral Force (Kips)**	**Percentage Increase**
	UDRM-DL	UDRM-DL 1800 Psi	7.0000	7.4319	7.2160	30.56%
		UDRM-DL 6192 Psi	7.5963	11.2456	9.4209	
		UDRM-DL 2400 Psi	9.8034	8.0853	8.9444	5.33%
		UDRM-DL 6192 Psi	7.5963	11.2456	9.4209	

In Table 1, there is self-comparison of different categories of High strength concrete (6192 psi) models as well as their comparisons with the corresponding Single Layered CFRP Low strength concrete models (1800 & 2400 psi). While in Table 2, there are comparison results of High strength concrete models with the corresponding Double Layered CFRP Low strength concrete models (1800 & 2400 psi). The data in both these tables is extracted from the aforementioned backbone curves and is expressed in the form of numerical data in terms of percentage increase which gives a better understanding of results.

5 Conclusions:

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

i. Upon comparison of the **CM** and **DRM – SL & DL** of HSC, Load carrying Capacity in the DRM-SL model was **increased** by **15.96%** for **SL** wrapping and **9.11% for DL** wrapping and upon comparison of the **CM** and **UDRM – SL & DL** of HSC, it was **increased** by **11.51%** for **SL** wrapping and **18.95 % for DL** wrapping.

ii. Upon comparison of the **CM** of LSC (1800 & 2400 Psi) and HSC Models (6192 Psi), Load carrying Capacity in the HSC model was **increased** by **35.45%** for **1800 Psi vs 6192 Psi** and **21.52%** for **2400 Psi vs 6192 Psi.**

iii. Upon comparison of the DRM-SL CFRP wrapped LSC models (1800 & 2400 Psi) and DRM-SL CFRP Wrapped HSC Models (6192 psi) Load carrying Capacity in HSC model was **increased** by **55.46%** for **1800 Psi vs 6192 Psi** and **15.74%** for **2400 Psi vs 6192 Psi**.

iv. Upon comparison of the UDRM-SL CFRP wrapped LSC models (1800 & 2400 Psi) and UDRM-SL CFRP Wrapped HSC Models (6192 Psi) Load carrying Capacity in the HSC model was **increased** by **27.54%** for **1800 Psi vs 6192 Psi** and **4.42%** for **2400 Psi vs 6192 Psi**.

v. Upon comparison of the DRM-DL CFRP wrapped LSC models (1800 & 2400 Psi) and DRM-DL CFRP wrapped HSC Models (6192 Psi) Load carrying Capacity in the HSC model was **increased** by **51.61%** for **1800 Psi vs 6192 Psi** and **30.74%** for **2400 Psi vs 6192 Psi**.

vi. Upon comparison of the UDRM-DL CFRP wrapped LSC models (1800 & 2400 Psi) and UDRM-DL CFRP wrapped HSC Models (6192 Psi) Load carrying Capacity in the HSC model was **increased** by **30.56%** for **1800 Psi vs 6192 Psi** and **5.33%** for **2400 Psi vs 6192 Psi**.

The results clearly show that there is a significant increase in load carrying capacity of the HSC models as compared to the LSC models as well as in the load carrying capacity of the HSC retrofitted models as compared to the HSC unretrofitted/control models. The existing bridges made of High strength concrete after revision of Building code need structural improvements in order to comply with the safe provisions of revised building code. The existing bridge piers when retrofitted with CFRP will show a considerable increase in load carrying capacity as it is evident from the results of this research. This will prolong the life of the bridge as well as the structure will be saved from future earthquakes of high intensity as well.

Hence, it is recommended that the existing bridge piers of HSC be retrofitted with Single or Double layer of CFRP to meet the present codal requirements instead of demolishing a whole bridge and constructing it again as per requirements of new Building codes. This will increase its load carrying capacity and also it will fulfill the criteria of revised building codes provisions.

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