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Research Article

Cyclic Behavior of Retrofitted Low- and High-Strength Concrete Scaled Bridge Piers under Quasistatic Loading

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Bridges are vulnerable to devastation in the earthquake, resulting in the closure of the whole transport system of the particular region. Generally, pre-Kashmir earthquake bridges in Pakistan were not designed according to present seismic zoning requirements. Therefore, it is critical to evaluate their seismic performance and accordingly enhance their strength, stiffness, and thus reliability. Seismic retrofitting of existing bridges with CFRPs (carbon fiber-reinforced polymers) may be planned for typical bridge types of Pakistan. High-strength concrete (HSC) is now widely used in bridge construction, and the seismic behavior of typical bridge piers being a key component needs to be assessed. This investigation aims to evaluate the seismic performance of HSC piers before and after retrofitting in association with the earlier research in Pakistan on low-strength concrete prototypes. An experimental program was executed wherein scaled-down (4 : 1) HSC (6192 psi) RC bridge pier prototypes with axial load at the top were subjected to quasistatic cyclic loadings (QSCLs) under controlled drifts. The damaged pier prototypes were retrofitted with CFRP sheets beside another set of undamaged retrofitted models. The samples were tested under QSCL against several drift levels ranging from 0 to 5%. Hysteresis loops were drawn for each sample. The tests were studied for the assessment of the structural behavior of the prototypes. The results for the control models, damaged retrofitted models, and undamaged retrofitted models of low-strength concrete (LSC, 1800 psi and 2400 psi) obtained from doctoral research by Ali and Iqbal were compared with corresponding models of high-strength concrete (6192 psi). The outcomes clearly show a noteworthy increase in lateral load carrying capacity, ductility, strength, and energy absorption on an increase in concrete strength and retrofitting of the prototypes. The numerical modeling of these piers was in consistence with the experimental results. When retrofitted with CFRP, the existing bridge piers will enable the bridge stock to withstand high-intensity future earthquakes and lessen their seismic vulnerability against prospective damages.

1. Introduction

Bridges are the vital elements of a transport network. In an earthquake event, they are the most vulnerable to damage resulting in the closure of the whole transportation system. Generally, bridges constructed in Pakistan do not meet the present seismic requirements. After October 8, 2005 earthquake, seismic zoning, and seismic hazard maps were modified and the Building Code of Pakistan (BCP-2007) with seismic provisions was enforced. Bridges built prior to 2005 were constructed in accordance with the West Pakistan Code of Practice for Highway Bridges (WPCPHB1967), wherein the earthquake considerations were nominal. This fact put these bridge structures at risk against newly recommended seismic zoning requirements [1, 2].

To reinforce the existing structures and to retrofit them for forthcoming challenges, a research was concluded to examine the behavior of reinforced concrete (RC) piers enwrapped with composites straps of fiber-reinforced plastic (FRP). Results established that RC piers showed noticeable enhancements in strength and translational ductility [3]. In addition, an investigation of short columns after wrapping with FRP composite tubes was finalized. Outcomes of this research revealed that the wrapping enhanced the capability

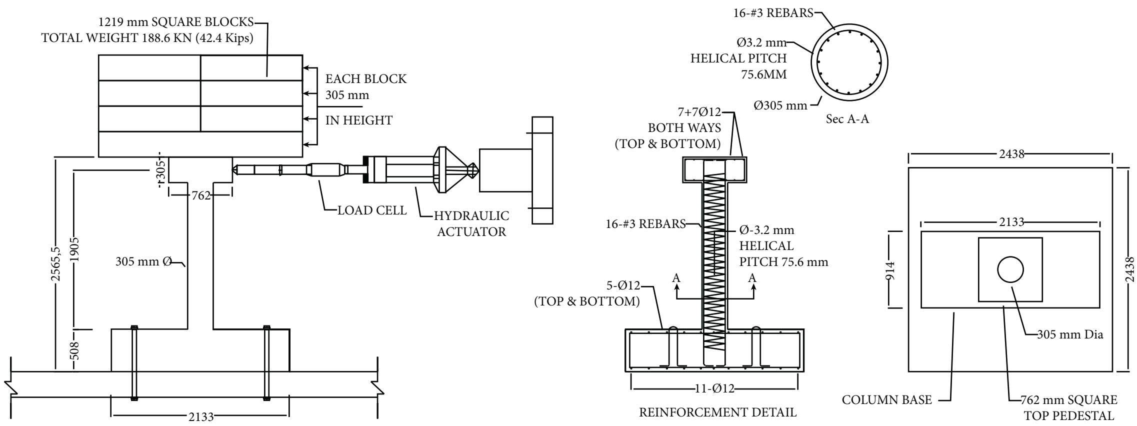

Figure 1: Investigational arrangement explaining the specimen sizes with top dead load arrangement and details of reinforcement used.

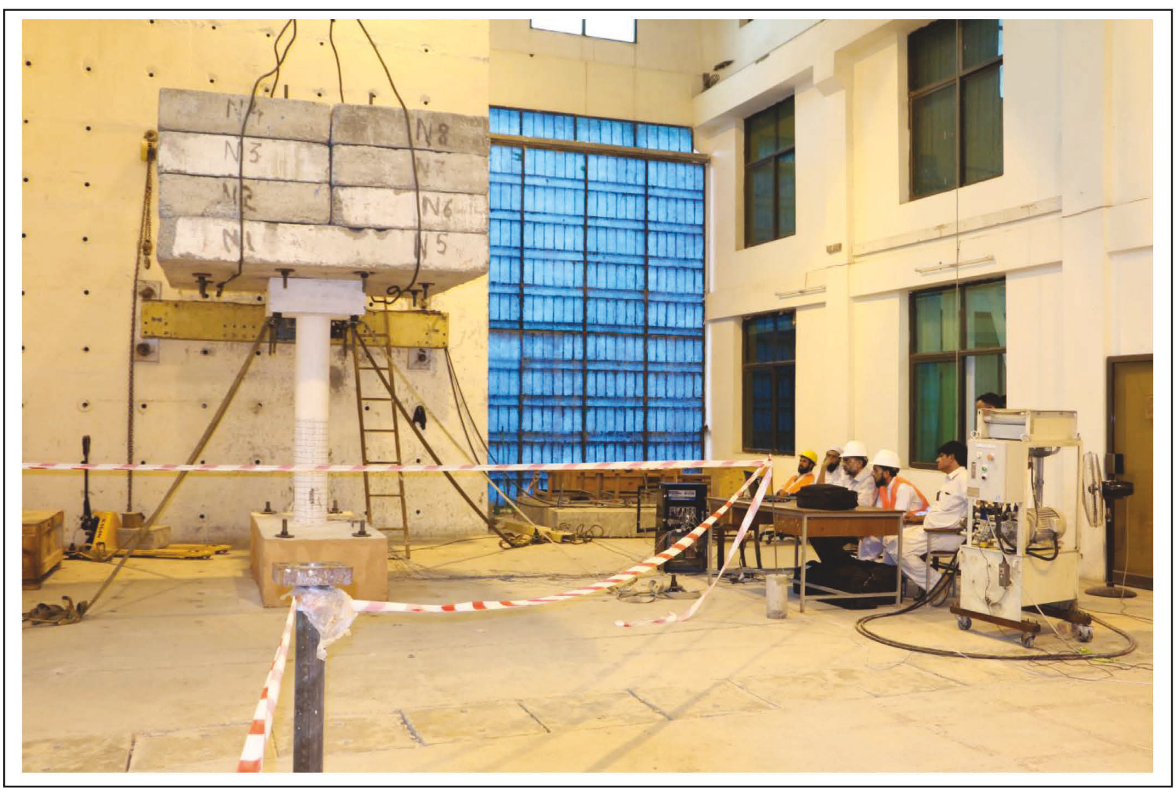

Figure 2: Test assembly setup with physical loading of 42.4 kips.

of tested RC columns in strain resistance, yielding, and energy dispersion [4]. In another study, surface-mounted FRP rods were bonded in the footings and the flexural capability of rectangular bridge piers was calculated. It was established that the flexural capacity of the piers was improved [5].

The properties of the materials used for confinement and the performance of confined cylinders were studied in the experimental investigations. The results concluded that columns were able to take 35% greater load when retrofitted with jacketing by pretensioned fiber-reinforced polymer materials and were able to take 400% additional load when RC columns were unconfined but retrofitted [6]. In order to warrant shear failure, a work was carried out on short columns. Here, eight columns with deficient transverse steel and with longitudinal reinforcement higher than the upper boundaries were considered. CFRP application was made to seven out of these eight models. All of them were subjected to a sustained compressive load in addition to a lateral quasistatic cyclical loading. FRP reinforcement entirely transformed the failure mechanism of these samples and increased both the strength and ductility [7]. In addition,

Figure 3: Damaged column, cracks, and spalling of concrete.

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

four scaled-down pier samples having 1800 psi and 2400 psi concrete were tested under quasistatic cyclical loading. It was established that the ability of 1800 psi and 2400 psi models to dissipate energy was in a similar range. The cumulative energy dissipation did not have any remarkable difference within these limits of the concrete compressive strength [1].

The samples cracked in the investigation [1] were repaired and retrofitted. Additional prototypes were prepared and retrofitted in their undamaged position and placed under the study to ascertain the outcome of retrofitting on the strength and energy dispersion of low-strength concrete (LSC) piers. The evaluation concluded that the properties of undamaged but retrofitted models improved in their strength and ductility [8]. The evaluation of seismic behavior of two high-strength concrete (HSC)-reinforced short columns installed with PVC pipe confinement, and three additional similar column samples of HSC with conventional hoop confinement, steel, and steel tubes, respectively, was conducted by short-cycle reversed loading tests. Through these strengthening methods, the energy dissipation and deformation capability of HSC samples were efficiently enhanced [9].

In another study, six square slender HSC columns were tested. CFRP wrapping with changing thicknesses of carbon fiber over the height of all the column samples was made. The curves for moment versus curvature were plotted for all of these column segments, which revealed that segments with greater thickness of carbon fiber sheets displayed a noticeable improvement in the performance of the column subdivisions. The lateral moment carrying capability of jacket-confined samples was improved from 48% to 100% with the envelope of 0.40 inch thick carbon fiber sheets. An analytical study was also conducted, analysis results were matched with the experimental records, and it was noted that the load versus deformation graphs showed an acceptable arrangement [10].

A research work was carried out by retrofitting reinforced concrete columns with CFRP sheets in the longitudinal direction affixing them to their base. The outcomes established the enhancement in the lateral strength and the effective stiffness of these reinforced concrete samples [11]. The performance of nonductile RC slender column specimens when enwrapped with carbon fiber-reinforced polymer and subjected to cyclic load test showed substantial enhancement in respect of translational ductility, load

Figure 5: Grinded and prepared surface of pier for CFRP application.

carrying capacity, the total energy dissolution, and failure process [12]. Another investigational effort was concluded to estimate the effectiveness of the use of CFRP applications to retrofit the nonductile joints of beams or columns. It was apprised that the application of one layer of CFRP sheet appeared more beneficial than two layers [13]. The use of CFRP for fortifying the columns in RC buildings was probed for the capacities and the benefits by considering deviation of concrete class, reinforcement percentage and strengthening skills by conducting quasistatic tests both for compressive loads and bending capability. It was established that CFRP applications are useful means to strengthen and retrofit RC structures due to the properties that they can comprehensively increase flexural properties, shear resistance, column confinement, and ductility [14].

It is studied that the similitude characteristics are not similar for static and dynamic testing [15]. In another research, reinforced concrete columns were subjected to hysteretic load and the result was concluded that the hysteric response of deficient columns may be increased by CF sheet

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

Figure 7: Testing of pier after the application of CFRP.

encasing being an efficient means to increase lateral confinement, strength, and ductility [16]. In a study, a crux of various analytical techniques for retrofitting in seismic regions by using FRP is presented [17]. In a research work, column samples were externally enwrapped with carbon fiber-reinforced polymer and were having a continuous compressive force along with a lateral load to perform quasistatic cyclic testing. The outcomes established that confining application of CFRP totally improved the failure mechanism of those samples [7]. An extensive research was made on efficient rehabilitation techniques for structures damaged after a historic earthquake. During experimental work, eight low-strength scaled-down (4 : 1) piers were modeled and four of them were wrapped with CFRP. The quasistatic cyclic and free vibration tests were performed on these models to envisage CFRP wraps' behavior and effectiveness [2]. In another work, analytical simulation and analysis of LSC scaled-down models of bridge piers were conducted. Outcomes demonstrate that when columns are retrofitted prior to the damaged state, the ductility of columns is increased and their energy dissipation capacity effectively enhanced without noticeable loss in stiffness [18]. In other studies, the reliability analysis of CFRP-confined concrete cylinders [19] and the performance of reinforced concrete circular columns wrapped with the CFRP and subjected to the axial load are represented very well with the analytical equations developed [20]. Similarly, the effect of CFRP, on seismic retrofit of short columns [7], on axial compressive strength [21], as a structural material [22], as an externally bonded reinforcement [23], on the behavior of inadequately detailed RC columns during an earthquake event [24], and on the residual performance of R.C. columns [25], has been studied by different researchers with promising results.

The bridges in the past have been constructed following WPCPHB1967. The concrete strength used in these structures was low to moderate level. Now with the implementation of the new building code with revised seismic provisions and modified seismic zonings, there is an immediate requirement to reinforce the standing bridge structures and especially their piers, being the most vulnerable parts of the structure, in order to resist more severe earthquake events. In a recent experiment [26] and numerical investigations [27], the energy dissipation behavior of HSC and CFRP retrofitted piers, which got damaged due to quasistatic loading, is presented. The current investigation has the main objectives to analyze and evaluate the lateral

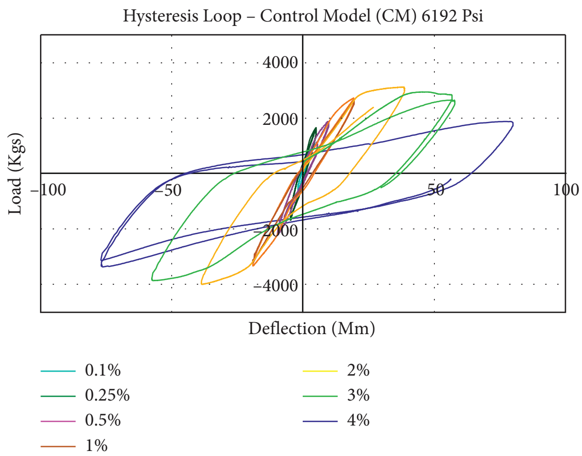

Figure 8: Hysteresis curves of the CM 6192 psi pier model subjected to different drift levels.

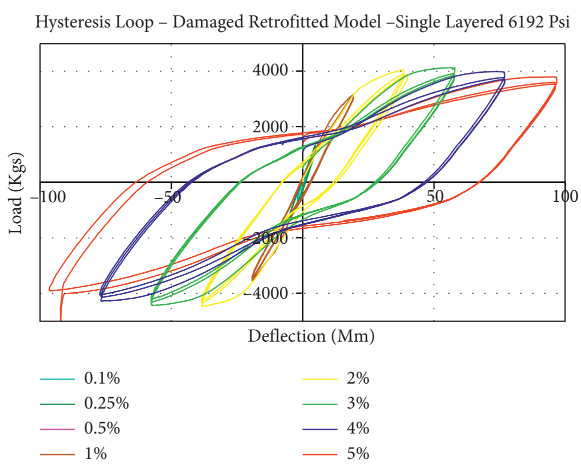

Figure 9: Hysteresis curves of the DRM-SL 6192 psi pier model subjected to different drift levels.

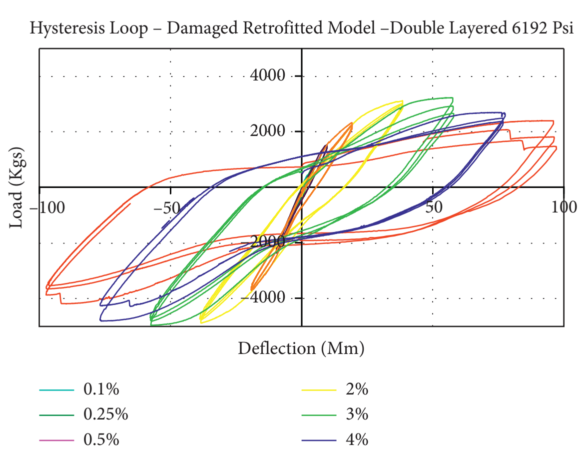

Figure 10: Hysteresis curves of the DRM-DL 6192 psi pier model subjected to different drift levels.

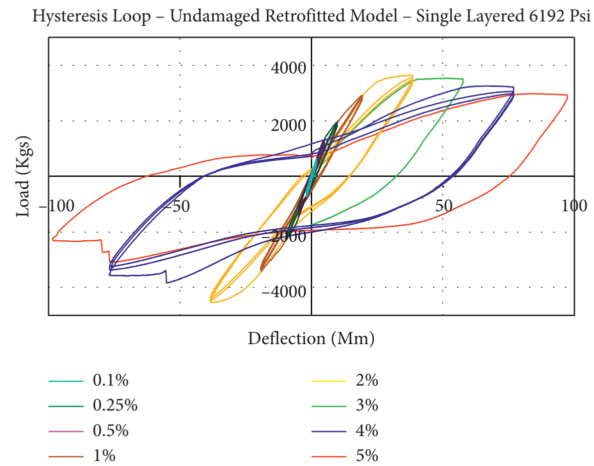

Figure 11: Hysteresis curves of the UDRM-SL 6192 psi pier model subjected to different drift levels.

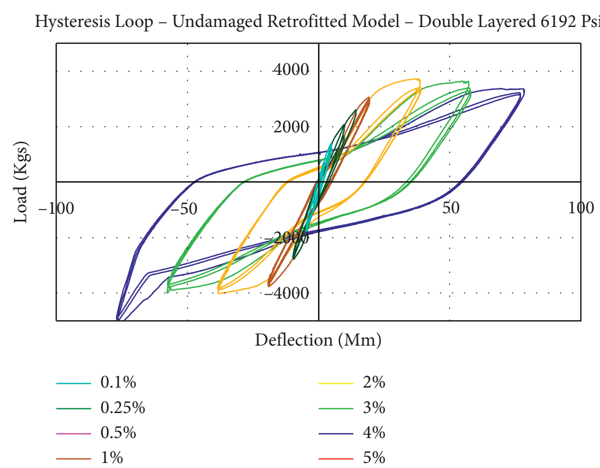

Figure 12: Hysteresis curves of the UDRM-DL 6192 psi pier model subjected to different drift levels.

load carrying capacity, equivalent stiffness, and equivalent damping of HSC model bridge piers when these are provided with CFRP retrofitting. This investigation also presents the evaluation of the behavior of low-strength concrete (1800 and 2400 Psi) bridge piers viz, namely, a high-strength concrete (6192 Psi) in respect of load carrying capacity, equivalent stiffness, and equivalent damping. The investigation work on low-strength concrete has already been carried out vide references [2, 8, 18]. The experimental outcomes of these investigators were analyzed and compared with the results of the present study. This research also covers the numerical simulation and evaluation of HSC bridge models retrofitted with CFRP to find out its effectiveness in increasing the strength of the piers. A comparison of results of simulated models for both of high-strength and of low-strength concrete models with experimental results shows that they are in acceptable limits. The results clearly illustrate a noteworthy rise in load carrying capacity of high-

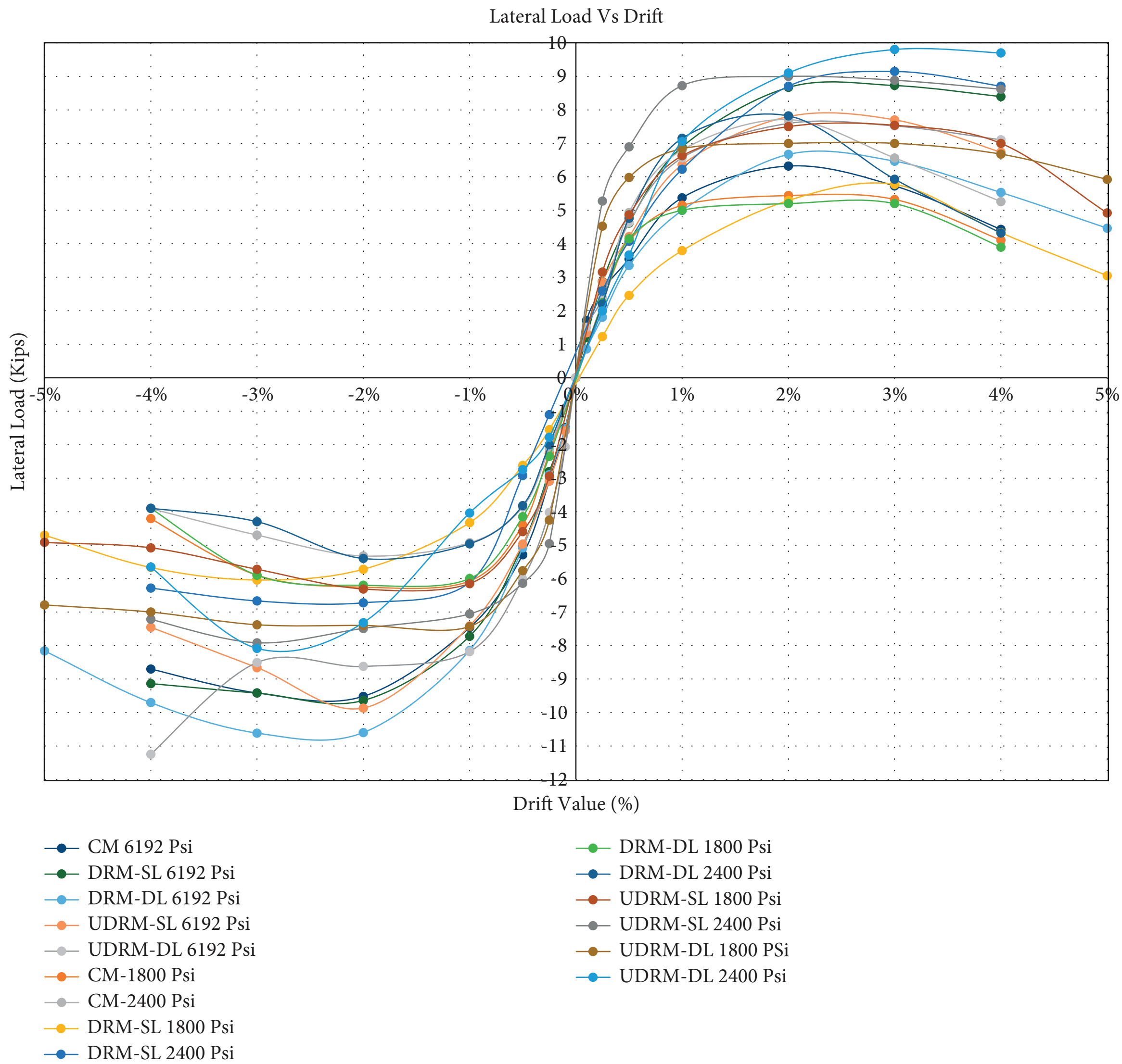

Figure 13: Lateral load vs drift: comparison of 6192 psi model backbone curves with those of similar work carried out by Ali [1] and Iqbal [2] with 1800 psi vs 2400 psi models.

strength concrete models, the minutiae of which are cited in subsequent sections.

2. Experimental Arrangement

All the experimental work was completed in the Civil Engineering Department of University of Engineering and Technology Peshawar, Pakistan, where satisfactory facilities and essential apparatus are available. The investigation work included quasistatic cyclic testing of Six (6) bridge pier samples with the following properties.

The model piers were prepared by scaling them down to 4 : 1 by similitude analysis [15] and then scheduled in experimentation as was performed by different researchers [1, 2]. These samples were having average concrete strength of 6192 psi. The steel used had 83000 psi yielding strength with an elastic modulus of 29,000,000 psi. A dead load of 42400 lbs was assembled on each prototype. The QSC test was performed on each specimen. Polymer (CFRP) sheets labeled HEX 103-C with a 0.40 inch (1.016 mm) thick fabric, 153000 psi strength in tension, and modulus of elasticity of 9400000 psi were externally applied in lower 24 in each of the retrofitted model. The comprehensive experimental arrangement with all the geometric information is given in Figure 1.

The representative concrete cylinder samples were tested for compressive strength, whereas the QSC testing was performed on each pier sample. The enhancement of the properties due to retrofitting of these scaled-down models was envisaged. To better visualize these improvement effects, the following testing schedule was conceded:

(a) Two HSC test samples were subjected to quasistatic cyclic loading tests with their unretrofitted state and were tested up to failure. These models are designated in the research as CM or control models.

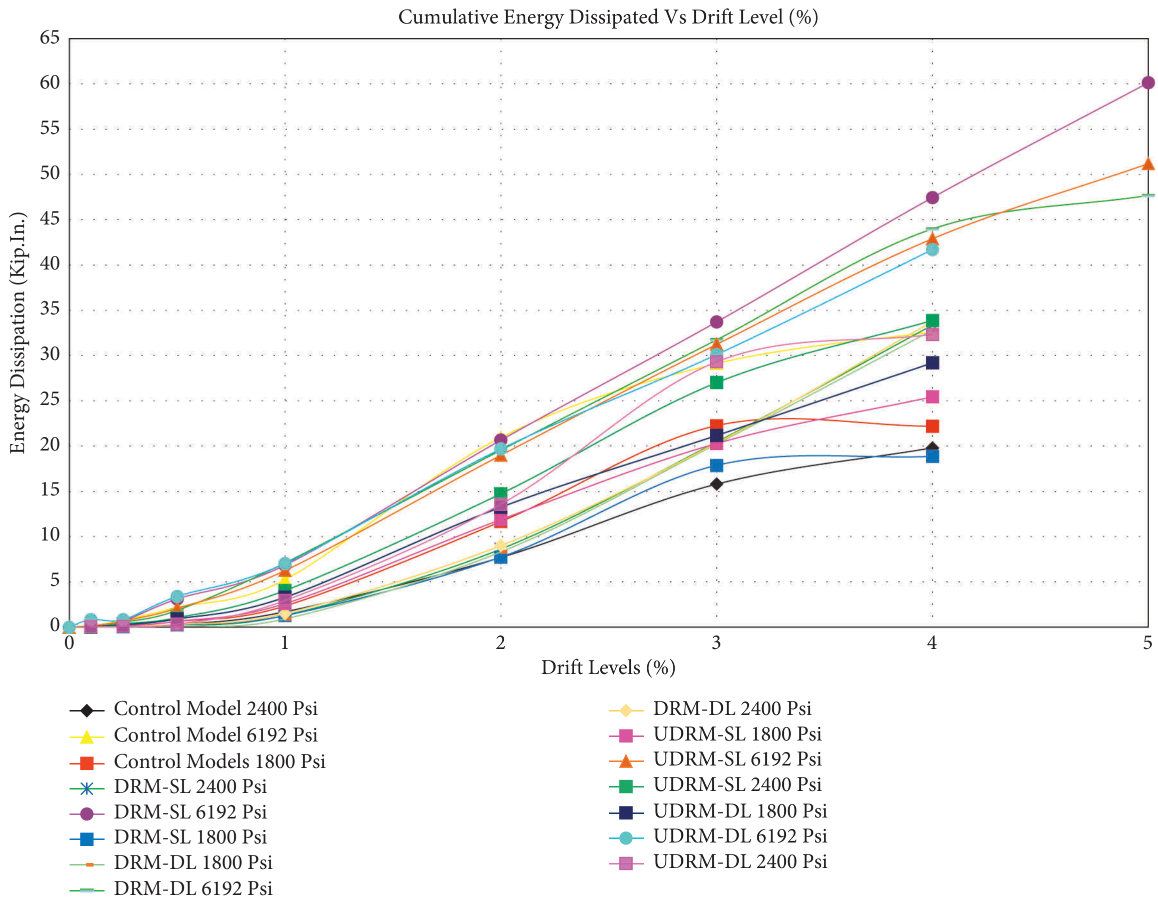

FIGURE 14: Cumulative energy dissipated vs drift—comparison of 6192 psi model curves [26] with those of similar work carried out by Ali [1] and Iqbal [2] with 1800 psi and 2400 psi models.

(b) These cracked models were restored, which constituted repairing of cracks with the cementitious mix, restoring their shape and retrofitting with CFRP. For one model, single layer of CFRP was used for retrofitting, which is referred as damaged retrofitted model—single layer (DRM-SL), while for the second sample, double layer of CFRP was used for retrofitting, 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 to assess strength, stiffness, and damping properties of the samples.

(c) Two additional models prepared with similar high-strength concrete (6192 psi) were applied retrofitting sheets in their original/unspoiled state, and then, quasistatic cyclic tests were performed on them. A sample was wrapped with one sheet cover of CFRP, which is referred to as undamaged retrofitted model—single layer (UDRM-SL), while two CFRP sheet covers were applied to the other model, which is referred as undamaged retrofitted model—double layer (UDRM-DL).

(d) QSCT was performed at different drift levels, i.e., 0 to 4% and 5% in some cases. The extent of 5% drift involved depending upon the failure criteria set for the models and the safety concerns due to the presence of a dead load of 42400 lbs over the specimens of the small diameter of one foot only subjected to repeated reverse cyclic loading. Thus, a potential threat of an accident to the laboratory equipment and to the staff working in the laboratory was present. The safety measures were adopted accordingly.

(e) After completion of QSCT on all the samples, IGOR Pro software was used to arrange the data recorded on the data logger in the format of spreadsheets.

The activities including test assembly setup, damaged column with cracks, and spalling of concrete, crack filling and repairing, preparation of surface, application of CFRP, and testing of the column after this application are illustrated in Figures 2–7, respectively. The cyclic lateral loading of the tests with the change in drift stages provided hysteresis curves for all the models. Hysteresis curves were separately shaped for each drift level, which are presented below in Figures 8–12. With the help of these hysteresis curves, backbone curves were generated.

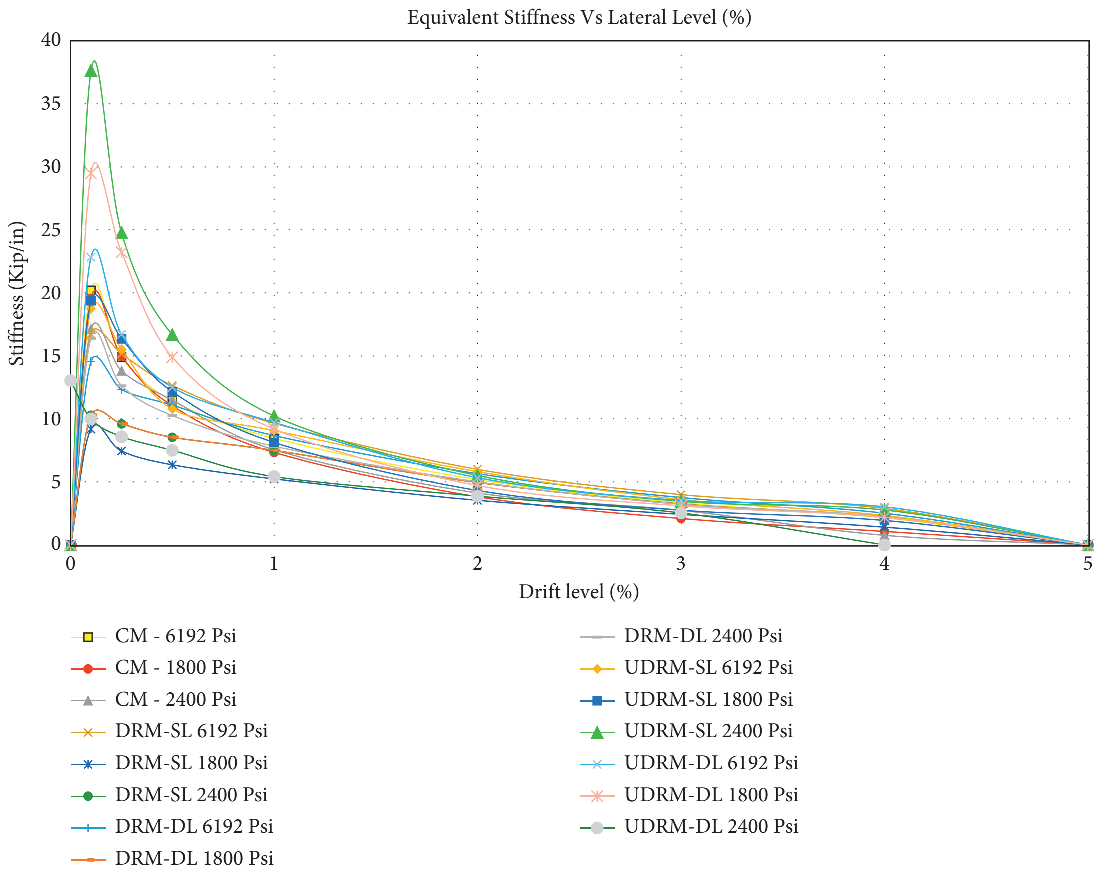

Figure 15: Equivalent stiffness vs drift—comparison of 6192 psi model curves with those of similar work carried out by Ali [1] and Iqbal [2] with 1800 psi and 2400 psi models.

3. Experimental Results

The statistics obtained from the investigational outcomes by the data collecting instrument data logger was analyzed with the help of a software named IGOR Pro, wherein it was organized in the form of spreadsheets and graphs were plotted. The number of tested specimens was six. The quasistatic cyclic load was applied to each sample with a varying range of drift increasing from 0% to 5%. The graphs accordingly portray the load carried/resisted by the model. The hysteresis curves are plotted by combining these graphs [26]. The peak value of each curve was marked and used to draw backbone curves. The backbone curves for representative control models, damaged retrofitted models, and undamaged retrofitted models for LSC (1800 psi and 2400 psi) were gained from previous work carried out by Ali [1], Khan et al. [8], and Iqbal [2] and have been analyzed in comparison with matching curves of HSC, i.e., 6192 psi (Figure 13).

The area under the hysteresis loop curves gives the value of energy dissipated. Energy dissipation values for different drift levels (0.1%, 0.25%, 0.5%, 1%, 2%, 3%, 4%, and 5%) for each model were the same as in recent research [26]. The energy dissipation values for control models, damaged retrofitted models, and undamaged retrofitted models of HSC and those of LSC gained from previous work carried out by Ali [1] and Iqbal [2] were compared and analyzed [26] to investigate the improvements made by CFRP (Figure 14) and are replicated here for reference.

Herein CM = control model, DRM = damaged retrofitted model, UDRM = undamaged retrofitted model, SL = single layer, and DL = double layer.

Equivalent stiffness k_e (kip/in) and damping were also determined in this research. For this purpose, necessary calculations were made on Excel sheets. In these calculations, values of drift level, displacements, and push and pull forces were used, and relevant formulae for evaluating the equivalent stiffness and damping values were applied. Graphs were then plotted between different drift levels and equivalent stiffness and damping, respectively. Curves obtained for HSC (6192 psi) were then compared with LSC (1800 psi and 2400 psi) (Figures 15 and 16). It is noted that the stiffness values for UDRM-SL 2400 psi and UDRM-DL1800 psi are on the excessive side while others are in consistency. It was further noted that the value of equivalent damping increased with the increase in drift level while it is approximately in the same zone for high-strength concrete.

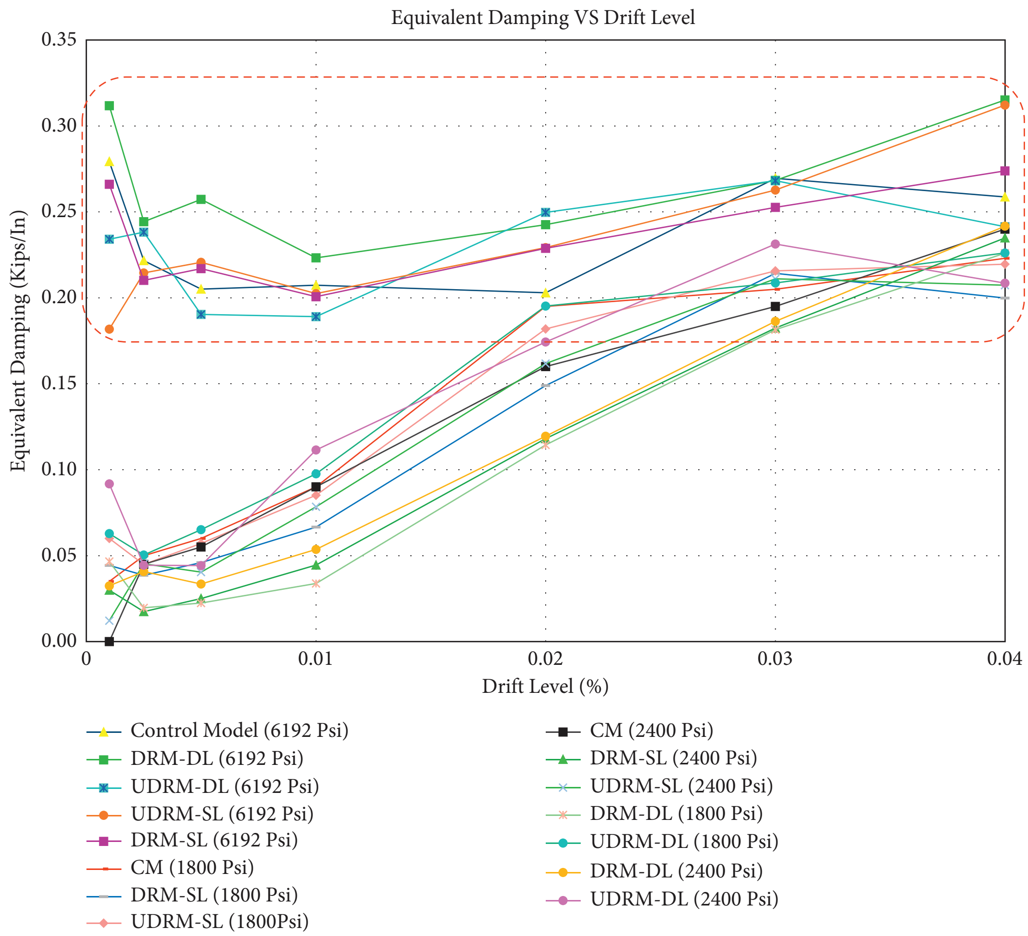

FIGURE 16: Equivalent damping vs drift—comparison of 6192 psi model curves with those of similar work carried out by Ali [1] and Iqbal [2] with 1800 psi and 2400 psi models.

TABLE 1: Material properties used in SiesmoStruct.

Description	Limits
Unconfined concrete	
Compressive strength (psi)	6192
Tensile strength (psi)	382
Strain at peak stress	0.0018
Confinement factor	1.0
Steel reinforcement	
Modulus of elasticity (psi)	29000000
Yield strength (psi)	83000
Fracture/buckling strain	0.067
CRFP	
Thickness (in)	0.04
Tensile strength (psi)	153000
Confinement factor	1.981
FRP jacket elastic modulus (psi)	9400000
FRP jacket ultimate strain	0.01
Radius of rounding corner (in)	1.50

It is obvious from the evaluation of different sets of high-strength concrete (6192 psi) models and their comparison with the corresponding single- and double-layered CFRP low-strength concrete models (1800 and 2400 psi) that the rise in the strength of concrete substantially increased the load carrying capacity, equivalent stiffness, equivalent damping, and energy dissipation of the samples.

4. Numerical Simulation of Bridge Pier Models

The numerical modeling of the high-strength concrete bridge pier models for assessing their dynamic properties was also made. The hysteretic performance, the lateral stiffness, and damping properties were assessed for the columns wrapped with CFRP layers. The model geometry, different dimensions, type, and magnitude of applied loading were the same as considered in the experimental work. The control specimen was modeled and analyzed through the finite element method (FEM) using the "SeismoStruct" software. Then, the retrofitting of the specimen was modeled by encasing it with CFRP layers and it was analyzed again for assessing the effectiveness and performance of confined concrete. The software is capable of accounting for different sorts of nonlinearity. Quasistatic cyclic loading was stimulated through the static pushover analysis. A dead load of 42400 lbs was applied on the top of the model. The horizontal load generated on the round model was applied in the form of incremental drift stages

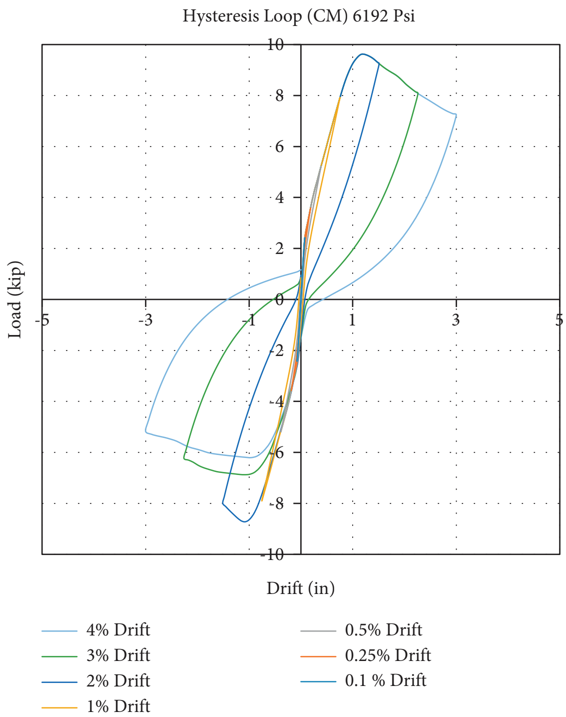

Figure 17: Hysteresis curve of control models (6192 psi).

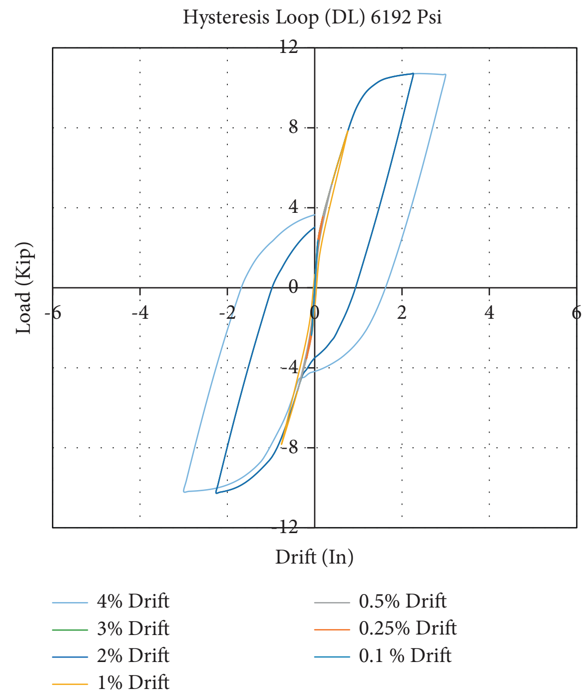

Figure 19: Hysteresis curve of double-layer models (6192 psi).

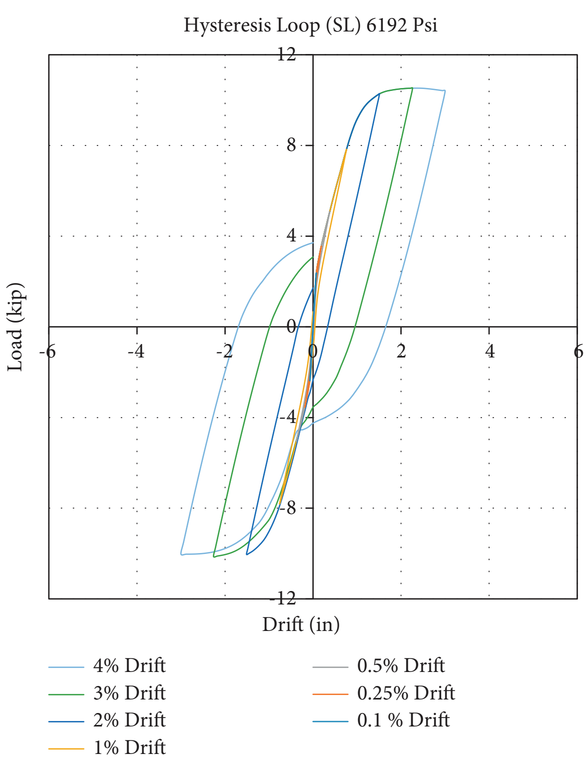

Figure 18: Hysteresis curve of single-layer models (6192 psi).

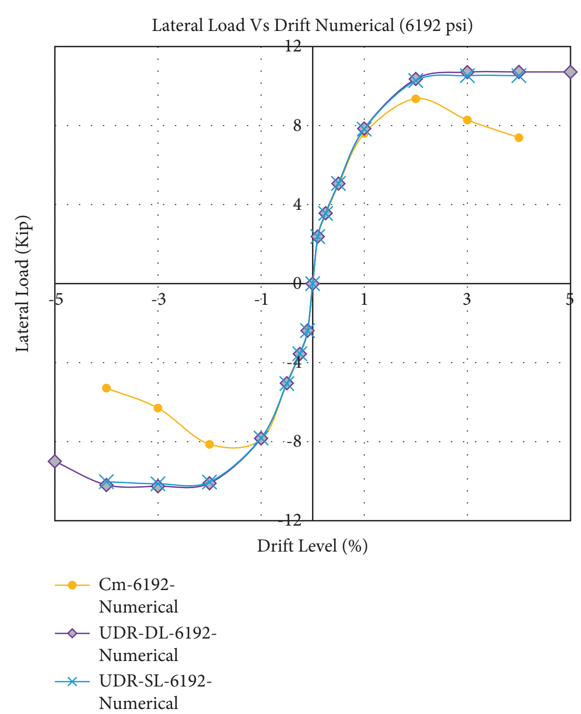

Figure 20: Comparison of lateral load vs drift (6192 psi).

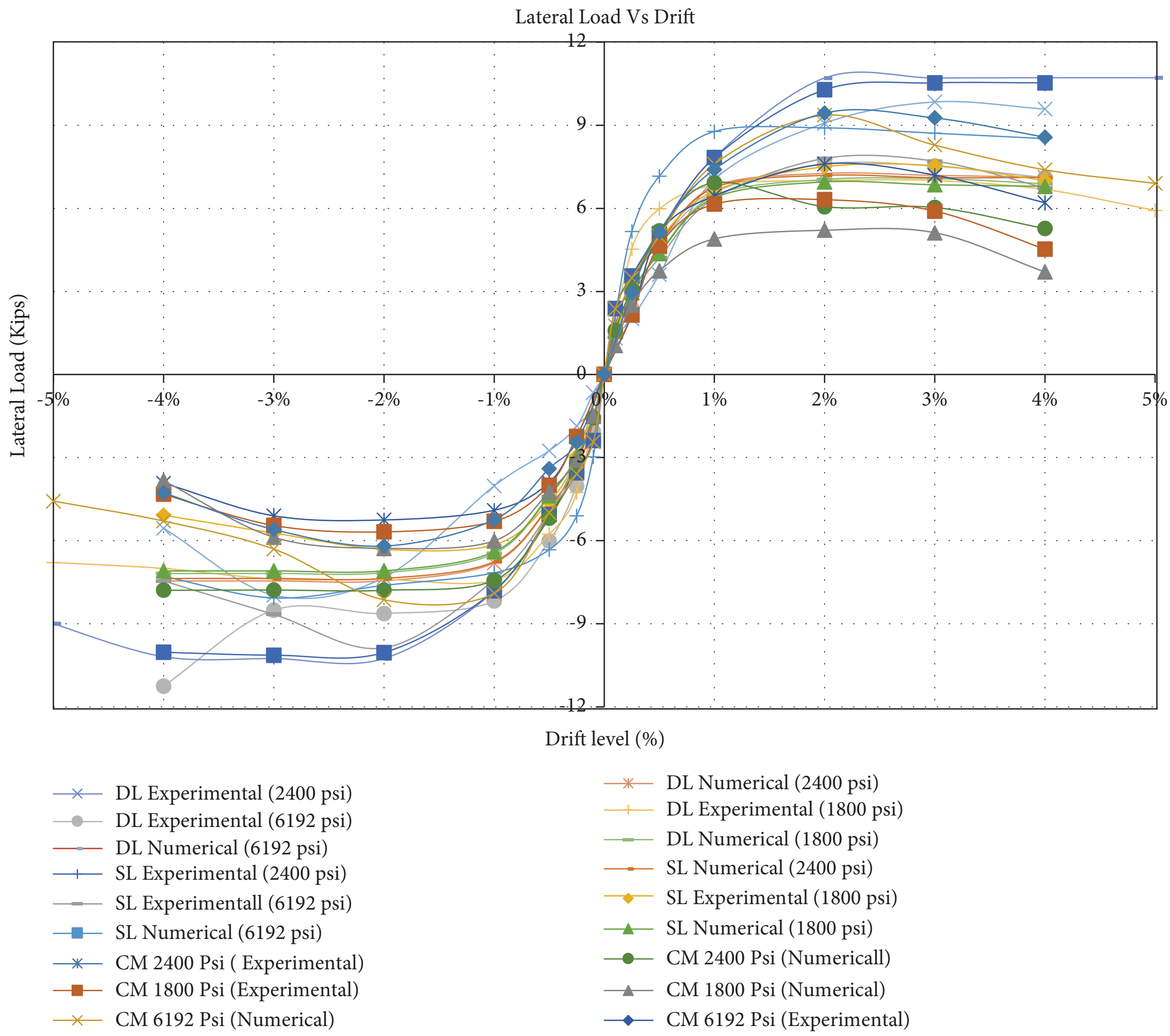

Figure 21: Lateral load vs drift—comparison of experimental vs numerical results.

on one specific track and then a returning force on the opposite path, thus establishing the hysteresis loop for every cycle.

Thirteen diverse features are present in SeismoStruct V6.5 to define material and loading conditions, which may be used by several methods to organize any number of materials and loads to be employed to the models. In the present research, the Mander et al. nonlinear concrete model (con_mat) was selected to describe the concrete in the core and in the cover while the pier was modeled as an inelastic force-based frame element type (infrmFB). Similarly, the steel was represented by the Menegotto–Pinto steel model (stl_mp). The parameters of nonlinear concrete material, the confinement factor, physical properties for the confined concrete model, and the type of element used for the model and the size element effect on the nonlinear behavior were based on the previous research conducted by the authors [18]. The properties of the materials considered in the software are arranged in Table 1.

5. SeismoStruct Results

Simulation of quasistatic cyclic load tests using pushover analysis was carried out. Subsequent to simulating the QSCL test, the accompanying actions were performed:

(a) The statistics obtained after the analysis of the model from SeismoStruct were rearranged in a manageable format and transferred to spreadsheets of Excel program.

(b) Hysteresis loop curves at various drift levels (in) against lateral load (kip) were individually plotted in Excel program. The damaged retrofitted model was not analytically analyzed; however, the curves for control model (CM), undamaged retrofitted model—single layer (UDRM-SL), and undamaged retrofitted model—double layer (UDRM-DL) for HSC have been displayed in Figures 17–19. The following information was derived from these curves:

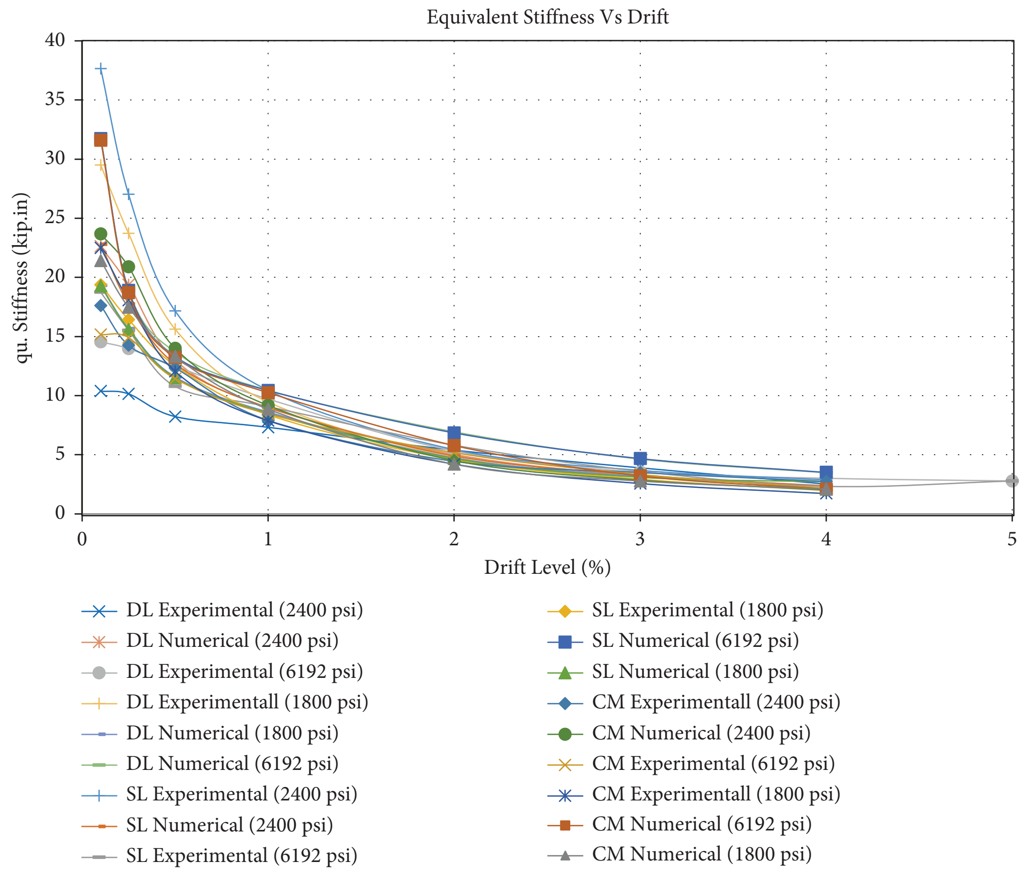

Figure 22: Equivalent stiffness vs drift—comparison of experimental vs numerical results.

(i) Maximum lateral load/strength of the column at each drift stage
(ii) Equivalent stiffness
(iii) Equivalent damping

(c) For the respective drift levels, curves were drawn for ultimate lateral loads for each drift value, as backbone curves, and are shown in Figures 20 and 21. The values for equivalent stiffness and equivalent damping were calculated in the same manner as in the experimental work and graphs, and Figures 22 and 23, respectively, are also plotted. The values for energy dissipation have been taken from recent research by Mustahsan [27] and reproduced here in Figure 24 for reference.

These curves of the control model (CM), undamaged retrofitted model—single layer (UDRM-SL), and undamaged retrofitted model—double layer (UDRM-DL) of HSC piers were compared with those of LSC specimens of the experimental work mentioned in this research and earlier research works [1, 2, 26] and earlier numerical works [18, 27] and checked for the increase with reference to the control models.

6. The Discussion on the Results

After the detailed study of experimental and numerical results discussed above, the following are the main outcomes:

(i) The percent increase in lateral load carrying capacity, equivalent stiffness, and damping in experimental results of the **DRM-SL and DL** and U**DRM-SL and DL** above those of **CM** for HSC 6192 Psi models is presented in Table 2.

A comparison of column #3 and column #4 of Table 2 reveals that for high-strength concrete the application of a single layer of CFRP is more efficient. Figure 16 demonstrates that the equivalent damping value remained approximately the same for high-strength concrete.

(ii) The summary of the experimental results of CM and DRM-SL and DL and UDRM-SL and DL of HSC 6192 Psi and of corresponding models of LSC (1800 and 2400 psi) in comparison of percent increase for lateral load carrying capacity, equivalent stiffness, and damping is given in Table 3.

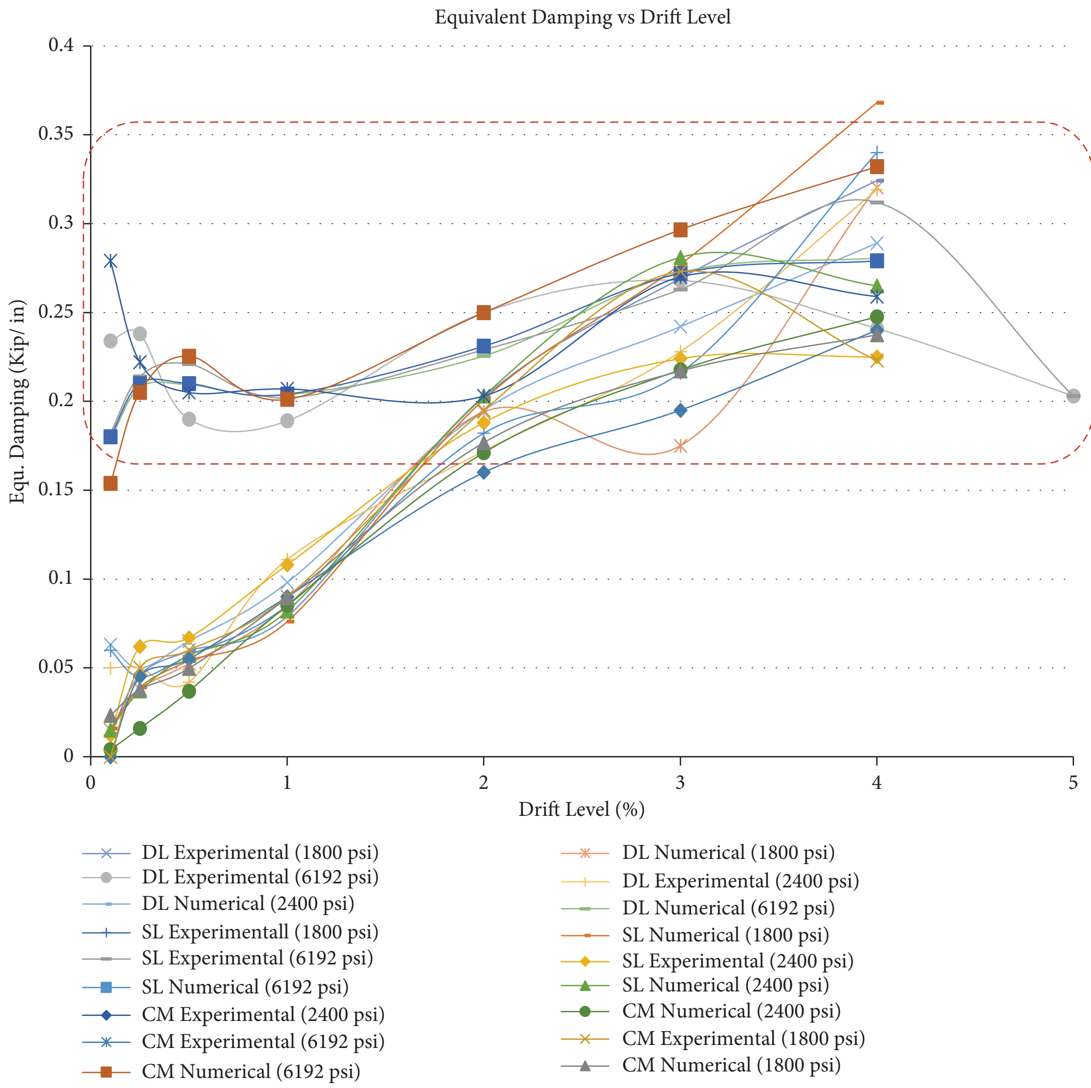

FIGURE 23: Equivalent damping vs drift—comparison of experimental vs numerical results.

Columns #3 and #8 of Table 3 exhibit the increase in properties on the increase of strength only. A comparison of column #3 and #4 of Table 3 with column # 4 and #5 and #11 of the same table, respectively, shows that the increase in properties is more prominent in 1800psi models, i.e., in low-strength columns.

Figure 16 further demonstrates that the value of equivalent damping increases with the increase in lateral drift for low-strength concrete models.

(iii) The comparison of numerical results of the control models (**CM)** and undamaged retrofitted models (U**DRM)-SL and DL** of HSC 6192 Psi for the percent increase of lateral load carrying capacity, equivalent stiffness, and damping is summarized here under in Table 4. Figure 23 further demonstrates that the equivalent damping value remained approximately the same for high-strength concrete.

(iv) The summary of the numerical results of CM and of SL and DL of HSC 6192 Psi and of corresponding models of LSC (1800 and 2400 psi) in comparison to percent increase for lateral load carrying capacity, equivalent stiffness, and damping is here under in Table 5.

The numerical analysis results are steady when compared with the experimental results due to the assumptions and parameters selected for analysis devised by different researchers. The results of the recent research studies [26, 27] also give the same trends. Figure 23 further demonstrates that the value of equivalent damping increases with the increase in lateral drift for low-strength concrete models. The percent increase in values above control model in low-strength concrete (1800 psi and 2400 psi) samples is more prominent as compared to their improvement in high-strength concrete (6192 Psi).

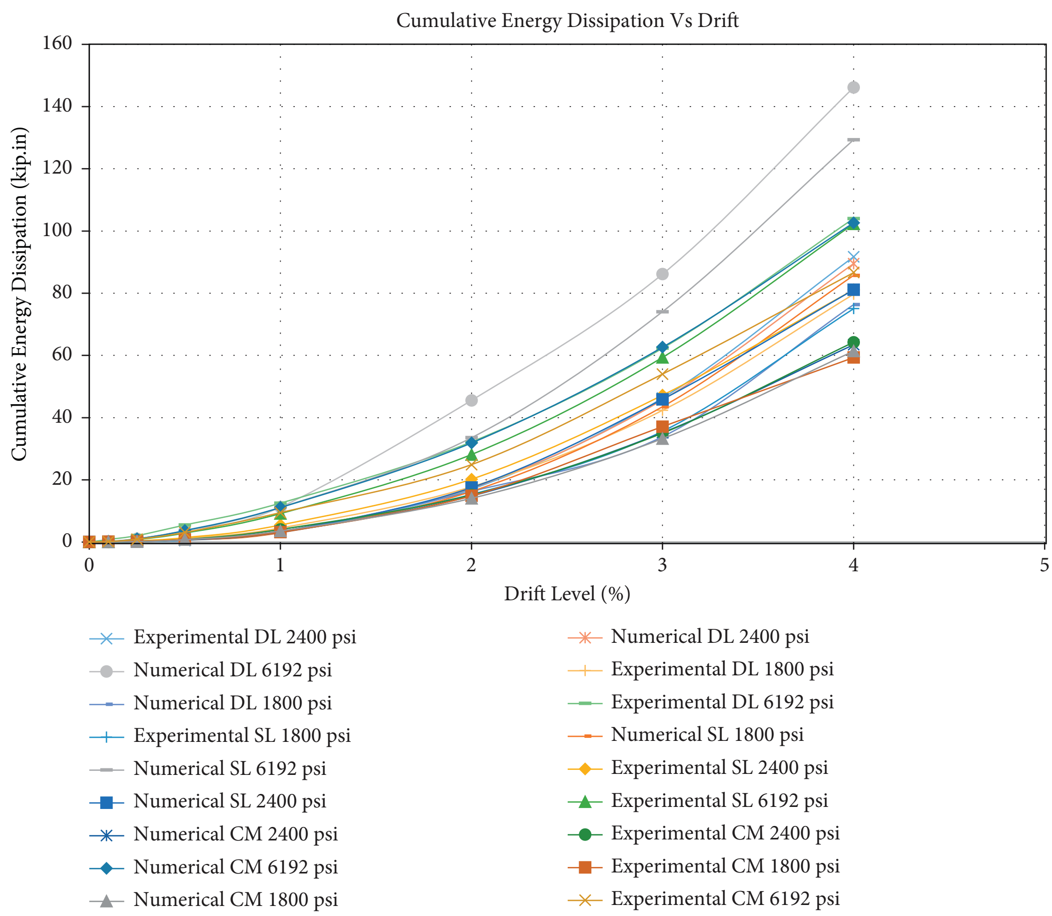

FIGURE 24: Cumulative energy dissipation vs drift—comparison of experimental vs numerical results.

TABLE 2: Percent increase above control model for HSC 6192 psi models in experimental results.

Sr. no.	Property	DRM-SL	DRM-DL	UDRM-SL	UDRM-DL
1	2	3	4	5	6
1	Lateral load carrying capacity	15.96	09.11	11.51	18.95
2	Equivalent stiffness	34.637	17.01	8.59	40.45
3	Equivalent damping	−1.93	12.85	11.78	-3.97

TABLE 3: Percent increase above control model for HSC 6192 vs 1800psi and 2400psi models in experimental results.

Sr. no.	Property	CM 6192 vs- 1800	UDRM-SL 6192 vs- 1800	UDRM- DL 6192 vs- 1800	DRM-SL 6192 vs- 1800	DRM- DL 6192 vs- 1800	CM 6192 vs- 2400	UDRM-SL 6192 vs- 2400	UDRM -DL 6192 vs- 2400	DRM-SL 6192 vs- 2400	DRM- DL 6192 vs- 2400
1	2	3	4	5	6	7	8	9	10	11	12
1	Lateral load carrying capacity	35.45	27.54	30.56	55.46	51.61	21.52	04.42	05.33	15.74	30.47
2	Equivalent stiffness	46.07	20.21	38.07	105.44	08.67	41.26	03.52	09.91	25.04	11.59
3	Equivalent damping	25.22	42.18	18.59	27.22	39.43	16.35	47.89	28.61	16.61	30.39

Table 4: Percent increase above control model for HSC 6192 psi models in numerical results.

Sr. no.	Property	UDRM-SL	UDRM-DL
1	2	3	4
1	Lateral load carrying capacity	16.32	18.04
2	Equivalent stiffness	4.61	4.52
3	Equivalent damping	05.88	05.65

Table 5: Percent increase above control model for HSC 6192 vs 1800psi and 2400psi models in numerical results.

Sr. no.	Property	CM 6192 vs-1800	UDRM-SL 6192 vs- 1800	UDRM-DL 6192 vs- 1800	CM 6192 vs-2400	UDRM-SL 6192 vs- 2400	UDRM-DL 6192 vs- 2400
1	2	3	4	5	6	7	8
1	Lateral load carrying capacity	31.75	48.20	47.01	35.26	43.22	43.20
2	Equivalent stiffness	43.25	60.19	62.40	31.05	40.08	40.70
3	Equivalent damping	86.92	19.53	37.31	92.86	63.93	36.50

7. Conclusions

Upon comparison of the experimental and numerical results of control models and CFRP wrapped **LSC** models (1800 and 2400 Psi) and CFRP wrapped **HSC** models (6192 psi) for lateral load carrying capacity, stiffness, and damping, it is concluded that

(i) All the properties effectively improve with the increase in the strength of concrete

(ii) The retrofitting significantly enhances all the properties of the piers

(iii) The effect of retrofitting is more prominent in case of concrete with low strength due to its effectiveness in the confinement

(iv) The outcome of double layer of CFRP sheets is more significant in low-strength concrete

(v) The result of single layer of CFRP retrofitting is more prominent in high-strength concrete

(vi) The effect of CFRP retrofitting is steady in numerical modeling as compared to that of the experimental results

(vii) The value of equivalent damping increases with the increased lateral drift for low-strength concrete models while it remained approximately the same for high-strength concrete prototypes

Therefore, it may be concluded that a significant enhancement in lateral load carrying capacity, equivalent stiffness, and equivalent damping is noticed in the HSC models when compared to those of LSC. This improvement is further enriched when HSC models are retrofitted. The numerical analysis further supports the experimental results.

The existing bridges made of low- and high-strength concrete need structural improvements after the revision of relevant seismic zones to comply with the revised seismic provisions. When retrofitted with CFRP sheets, the bridge piers showed a considerable growth in lateral strength, ductility, stiffness, and energy absorption as evident from the results of this research. This will enable the bridge structure to withstand high-intensity future earthquakes and lessen their vulnerability against prospective damages. Therefore, it is suggested that the available bridge stock may be checked for the capacity of their piers to meet with the seismic demand and may be retrofitted with CFRP to comply with the contemporary seismic zoning requirements instead of their replacement with new structures.

Data Availability

Data supporting the results of this study are available with the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The energy dissipation, equivalent stiffness, and damping were calculated in Excel sheets using relevant equations. The necessary calculation notes (Appendix A) describing the procedure used here with sample calculation sheets as Appendices B and C along with supporting Graph 1 for 1% drift for DRM-SL have been added for ready reference. (*Supplementary Materials*)

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