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Testing of CFRP Retrofitted RC Circular Hollow Bridge Column under Seismic Demand

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Abstract: Bridges are considered as life line structures. During an earthquake, dynamic forces induce inertial force into the structure which results in damage to lateral load resisting members, which are typically piers in bridges. Hollow bridge columns are required when longer spans are constructed or taller piers are needed or both. The hollow piers are subjected to high seismic demand, hence it is essential to evaluate their seismic performance. In this research the energy dissipation capacity of CFRP retrofitted RC circular hollow bridge column under seismic demand has been calculated. A representative prototype dimensions were established from the available bridge drawings and a scale down hollow column model was prepared using similitude analysis. The model column was subjected to unknown damage. The damaged model was then retrofitted by using CFRP wrap. The time period of the model column was calculated and the retrofitted column was subjected to quasi-static cyclic testing. The energy dissipated per cycle and the cumulative energy dissipated was calculated from the load displacement data. The energy dissipation data of retrofitted hollow column was compared with energy dissipation data of solid circular and retrofitted solid circular column data of previous researchers and an R-Factor value for hollow bridge column was also proposed.

Keywords: *CFRP, Energy dissipation, Hollow bridge column, Seismic demand, Quasi-static cyclic testing*

1 Introduction:

Urban development is taking place at a very faster rate across the world. One of the challenges of expansion and development of the cities is to have a reliable network of highways for efficient flow of traffic. In order to solve this problem elevated highways and interchanges have been constructed across the world. Such construction can be seen in developed countries like Japan, Thiland, USA and Europe. In recent years in Pakistan, Karachi is undergoing through a phenomenal urban growth in which elevated expressways are constructed. In such projects bridges are the key infrastructure elements. Circular reinforced concrete bridge piers are the best choice for such bridges because they utilize less space for construction therefore they become economical and practically feasible. Within circular piers, hollow bridge piers are constructed when longer spans are constructed or taller piers are needed or both.

October 8, 2005 Earthquake has showed that Pakistan lies in high seismic region. Due to absence of bridge design code in Pakistan, bridges are designed on various other code which either suit us or not. Hence it is necessary to study our typical bridge system to evaluate their seismic performance. Energy dissipation capacity of different types of reinforced concrete bridge columns vary from each other due to shape, size and boundary conditions. Single circular hollow RC columns are one of the important classes of sub-structure system in bridges that resists the earthquake induced forces. In this research the energy dissipation capacity of circular hollow RC columns is studied by fabricating scale down model in Earthquake Engineering Lab and testing it under cyclic loading. Various seismic parameters have been studied and the data collected has been used to arrive to quantifiable numbers of energy dissipation for circular hollow RC columns.

2 Similitude Analysis:

2.1 Study of Bridge Drawings:

For similitude analysis bridge drawings of the two bridges located in the KPK province were studied. The first bridge was located in District Kohistan, Dasu and the second bridge was located in besham. The hollow column detail of the two bridges is summarized in the table given below:

Table 1: Dasu and Besham bridge pier details

Parameters	**Dasu Bridge**	**Besham Bridge**
Pier Height (ft)	49.2	50.5
Pier Diameter Internal (ft)	14.1	9.9
Pier Diameter External (ft)	18.0	15.1
Long. Reinforcement (Nos)	232	150
Long. Reinforcement,bar dia (in)	1.26	1.00
Lon. Reinforcement Ratio	0.0202	0.0094
Tran. Reinforcement,bar dia (in)	0.625	0.375
Spiral Pitch (in)	4.0	6.0
Concrete Cover (in)	2.00	2.00
Dead load on column top (tons)	2237	982.4
Concrete Strength (psi)	3000	3000
Steel Strength (psi)		

2.2 *Selection of Scale Factor:*

For selecting scale factor different parameters of the model column like height, Internal and External Diameter, Axial load coming on column top, longitudinal and transverse reinforcement diameter etc were calculated from prototype by selecting a scale factor within range from 4 to 8. The scale factor was selected in such a way that it was manageable in terms of cost and time and that it was not beyond the limitations of lab. The minimum diameter of longitudinal reinforcement available in market was 5.28 mm while for a scale factor of 6 minimum diameter came out to be 5.33 mm hence scale factors greater than 6 were neglected. Similarly for a scale factor of 4 the model column height came out to be 12.6 ft and the mass to be provided on column top came out to be 61.4 tons. Provision of 61.4 ton mass on column top was practically impossible and to cast column of 12.6 ft height was also not possible. Hence after detail analysis of different parameters of column against various scale factors between 4 to 8 an scale factor of 6 was chosen for the model column.

2.3 *Establishment of model:*

In order to establish dimensions and material properties of model first dimensions and material properties of representative prototype from drawings of dasu bridge and besham bridge were established. The dimensions of the representative prototype were adjusted keeping in view the lab constraints and fabrication limitations and then the model dimensions were established. However the limitations did not deviated the original model and the model still represented the actual hollow column of the bridges constructed in Pakistan. The established dimensions and material properties of prototype and model hollow column are provided in the table given below.

Table 2: Established dimensions and material properties of prototype and model column

S#	Parameters	Bisham Bridge Pier	Dasu Bridge Pier	Prototype (Adjusted Dimensions)	Model
					Scale F= 6
1.	Pier Height (ft)	50.5	49.2	41.0	6.83
2.	Axial Load (tons)	982.4	2,237.2	980	27.2
3.	Pier Diameter Internal (ft)	9.8	14.1	10.5	1.75
4.	Pier Diameter External (ft)	14.4	18.0	15.0	2.5
5.	Lon. Reinforcement (No. of Bars)	150	232	126	126
6.	Lon. Reinforcement, bar dia. (in)	1.00	1.26	1.26	0.21(5.3 mm)
7.	Lon. Reinforcement Ratio	0.0094	0.0202	0.0121	0.0121
8.	Tran. Reinforcement, bar dia. (in)	0.375	0.625	0.625	1.0142 (Approx.3mm)
9.	Spiral Pitch (in)	6.0	4.0	6.0	1.0
10.	Concrete Cover (in)	2.00	2.00	2.00	0.33 (9 mm)
11.	Concrete Strength (Psi)	3,000	3,000	3,000	3,000
12.	Yield Strength (Psi)	50,000	60,000	60,000	60,000

3 Fabrication and Retrofitting of Model Column:

The fabrication of model column was carried out in three steps. Ist the column base was casted, then the hollow column was casted and at the end the pedestal was fabricated. The model hollow bridge column was subjected to unknown damage and then retrofitted. The retrofitting was carried out using carbon fiber reinforced polymer (CFRP) sheets. CFRP wrapping of bottom half length of the column was carried out. The dimensions and material properties of base, hollow column and pedestal are provided in the table given below:

Table 3: Dimensions and material properties of base, hollow column and pedestal

Parameter	Base	Hollow Column	Pedestal
Size	9ftx4ftx2ft	Outer dia=30in Inner dia=21 in	5ftx5ftx1.5ft
Long. Reinf	#4@ 3in c/c	Out.Dia=83bars In.Dia= 53 bars	#4@10in c/c

Trans. Reinf	#4@10inc /c	3 mm, 1in pitch	#4@10in c/c
Mix Ratio	1: 2.7: 3.4	1:1.5:3	1:1.5:3
W/C Ratio	0.58	0.62	0.58
Aggregat e size	¾ in down	Pan Crush	¾ in down
Avg. Strength	3808 psi	3404 psi	2311 psi

4 Experimental Setup:

4.1 Free Vibration Testing:

First the model column was subjected to free vibration testing when it was fully loaded. In the testing the mass on the top was moved with a sudden initial force and the column was allowed to move freely and then the vibration data was recorded. The force was provided by a person who would jump on the column top and would stand still until the data was recorded. The data was recorded for 10 to 20 seconds using DR-4000 data acquisition system and the data was processed using DADisp Software.

4.2 Quasi-static cyclic Testing:

Cyclic testing was performed in the displacement control mode. The lateral cycles were performed by means of 50 ton hydraulic actuator and lateral displacement was measured by means of displacement transducer. The testing was performed using the protocol described in table 4. The testing frequency was fixed at 150 seconds per cycle of drift which corresponds to 0.0067 Hz for a cycle. The testing was continued until 20% reduction in strength was observed.[5],[6]

Table 4: Test protocol used for quasi-static cyclic testing

Drift	No. of Cycles
0.10%	1
0.25%	2
0.5%	2
1%	2
2%	2
3%	2
Total	**11 cycles**

5 Experimental Results:

5.1 Free Vibration Results:

Free vibration testing was conducted in order to calculate time period and damping ratio[3]. The time period for the column in North-South (N-S) direction was calculated to be 0.24 seconds while for East-West (E-W) direction the time period was 0.35 seconds. The damping ratio for North-South direction was found to be 1.28% while for East-West direction the damping ratio was 1.37%.

5.2 Quasi-static cyclic Testing Results:

5.2.1 Observations during testing:

The testing began with one cycle of 0.1% drift followed by 2 cycles each of 0.25%, 0.5% drift. Minor circular cracks began to appear in the CFRP wrap at 0.25% and 0.5% drift.

At the first cycle of 1% drift the CFRP wrap bursted from the west side of the column both in horizontal and in vertical direction.

At the 2nd cycle of 1% drift the CFRP wrap further bursted and was removed from the column in horizontal direction from the north face. Spalling of concrete at the column base also started at the 2nd cycle of 1% drift.

Figure 1: Removal of CFRP wrap horizontally from north face

Figure 2: Spalling of concrete at the 2nd cycle of 1% drift

At the Ist cycle of 2% drift the CFRP wrap removed from the column in a circular pattern approximately to a height of 12 inches as shown in figure. Spalling of concrete also increased and relatively large pieces of concrete were removed from the base of the column, which made the horizontal and spiral reinforcement visible. At 1% drift spalling of concrete took place but large portion of the concrete was not removed while at 2% drift large pieces were removed and reinforcement became visible.

At 2 % drift buckling of bars also occurred at the south face. For south face of the column the force dropped from 8 tons to 4 tons when the drift was changed from 1% to 2% whereas for north face the force kept on increasing up to 13 tons.

Figure 3: Spalling of concrete and buckling of rebars at 2% drift

At the Ist cycle of 3 % drift the maximum force for south face stopped at 4 tons whereas for north face the maximum force kept on increasing upto 17 tons. 12 Nos of bars ruptured at the end of Ist cycle of 3% drift. At north face the column was in a position to take more load but the cyclic testing was stopped at the Ist cycle of 3% drift because the column had hollow x-section and the concrete at the net x-section had failed, the bars had also buckled and ruptured and relatively less area of concrete was available to resist the lateral loading. Further increase in loading might have resulted in the collapse of whole system therefore further loading was stopped.

Figure 4: Ruptured bars at 3% drift

From the analysis of the data plotted for hysteresis curve, different parameter like initial cracking, initial yield and yield point for south and north face of the column were established. These parameter were used to calculate displacement ductility, uncracked stiffness and cracked stiffness etc. These values are summarized in the table given below.

Table 5: Values of cracking, initial yield and yield of retrofitted model column

Item	**Values for South Direction**	**Values for North Direction**
Disp. Ductility	2.2	1.84
P_c	14 Kips	11 Kips
u_c	0.2% (4.16 mm)	0.28% (5.81 mm)
k_{uc}	85.36 Kip/in	48.03 Kip/in
P_{yo}	18 Kips	18.5 Kips
u_{yo}	0.5% (10.41 mm)	0.58% (12 mm)
k_{cr}	43.9 Kip/in	38.94 Kip/in
P_y	20 Kips	24 Kips
u_y	1.1%	1.06 % (22.07 mm)

5.2.2 Energy Dissipated:

The load and deformation data obtained from quasi-static cyclic testing was used to plot the hysteresis curves for each cycle of drift as shown in the figure given below:

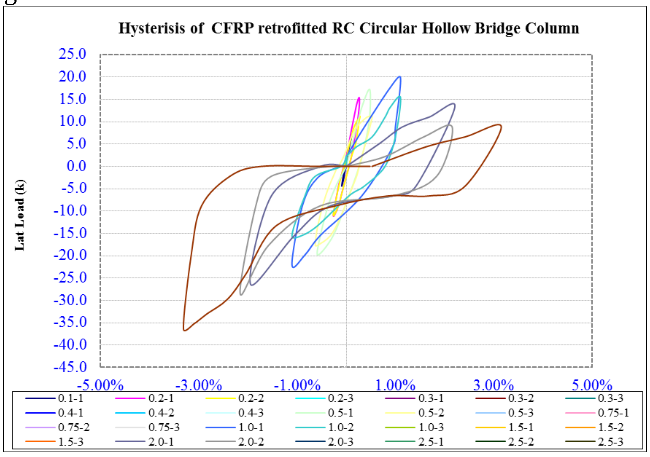

Figure 5: Hysteresis of CFRP retrofitted RC circular hollow bridge column

The values of energy dissipated and cumulative energy dissipated are shown in the table given below. The energy dissipated per cycle and cumulative energy dissipated is also plotted**Error! Reference source not found.**.

Table 6: Values of energy dissipated and cumulative energy dissipated

Drift	**Cycle**	**Energy Dissipated per cycle (k-in)**	**Cumulative Energy Dissipated (k-in)**
0.10%	1	0.14	0.14
0.25%	1	1.79	1.93
	2	1.53	3.46
0.50%	1	7.22	10.68
	2	7.06	17.74
1.00%	1	21.53	39.27
	2	15.21	54.48
2.00%	1	36.61	91.09
	2	32.95	124.04
3.00%	1	63.3	187.34

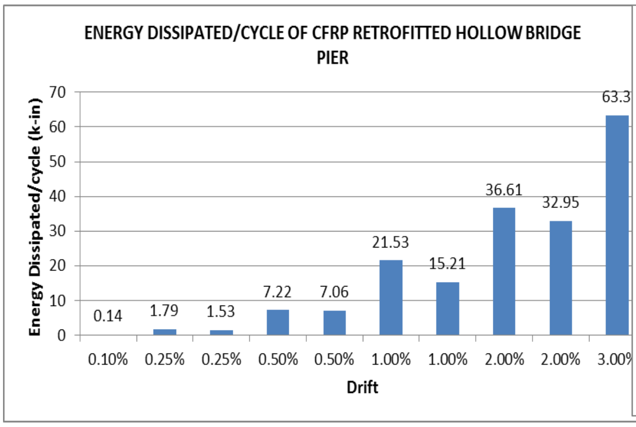

Figure 6: Energy dissipated per cycle of CFRP rtrofitted hollow bridge pier

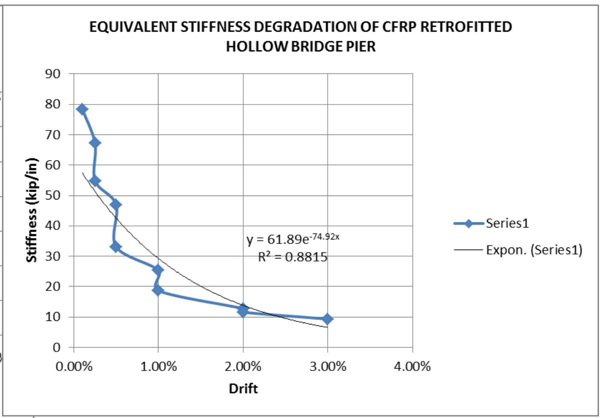

Figure 8: Equivalent stiffness degradation of CFRP retrofitted hollow bridge pier

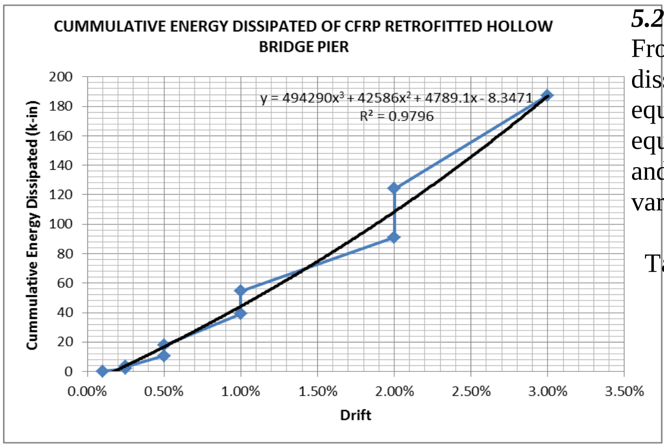

Figure 7: Cumulative energy dissipated of CFRP retrofitted hollow bridge pier

5.2.3 *Stiffness Degradation:*

The values of the equivalent stiffness are shown in the table given below. The stiffness degradation curve for the CFRP retrofitted hollow bridge pier plotted from the equivalent stiffness data is also shown in the figure given below.

Table 7: Equivalent Stiffness values of CFRP retrofitted hollow bridge pier

Drift	Stiffness (Kip/in)
0.10%	78.37
0.25%	67.18
0.25%	54.84
0.50%	46.99
0.50%	33.08
1.00%	25.33
1.00%	18.66
2.00%	12.76
2.00%	11.61
3.00%	9.33

5.2.4 *Equivalent Damping:*

From the values of equivalent stiffness, energy dissipated and from input energy to the system the equivalent damping [6] was calculated. The values of equivalent damping calculated at various drift levels and the graph showing the equivalent damping at various drift levels is given below.

Table 8: Equivalent damping values at various drift levels

Drift	ξ_e
0.1%	0.047
0.25%	0.11
0.25%	0.116
0.50%	0.143
0.50%	0.18
1%	0.198
1%	0.19
2%	0.189
2%	0.174
3%	0.184

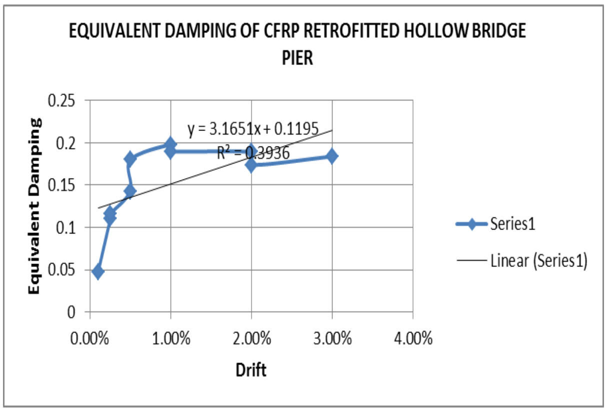

Figure 9: Equivalent damping of CFRP retrofitted hollow bridge pier

5.3 Comparison of Energy Dissipation (Hollow vs Solid Column):

5.3.1 Energy Dissipated per cycle:

Research has been conducted in Pakistan on the energy dissipated by solid circular bridge piers [2] and CFRP retrofitted solid circular bridge piers under seismic demand[4] by various researchers previously. Their research provided an opportunity to compare the energy dissipated per cycle data of CFRP retrofitted hollow pier with solid circular and CFRP retrofitted solid bridge piers. The solid circular bridge pier was declared as control model. The CFRP retrofitted solid bridge pier was named as retrofitted model and the CFRP retrofitted hollow bridge pier was named as retrofitted hollow model. The retrofitted model and the retrofitted hollow model were first tested by cyclic loading till failure and then the damaged models were retrofitted. The control model and the retrofitted model were casted using a scale factor of 4 whereas the retrofitted hollow model was casted using a scale factor of 6 therefore the comparison of energy dissipated per cycle among the models was not possible. The energy dissipated per cycle by the models was converted into the energy dissipated by the prototype using respective scale factors. Then energy dissipated per cycle per unit net x-sectional area of control prototype, retrofitted prototype and retrofitted hollow prototype was calculated and comparison of the energy dissipated per cycle among the prototypes was done. From the comparison it was concluded that the energy dissipated per cycle by retrofitted hollow prototype was greater than the control prototype and retrofitted prototype. The energy dissipated per cycle of control model, retrofitted model, retrofitted hollow model and of control prototype, retrofitted prototype and retrofitted hollow prototype is provided in the tables given below.

Table 9: Energy dissipated per cycle of drift of control model, retrofitted model and retrofitted hollow model

Concrete (psi)	**CFRP Layers**	**Energy Dissipated per cycle of Drift (Kip-in)**										
		Control Model (1:4)				**Retrofitted Model (1:4)**				**Retrofitted Hollow Model (1:6) (3400 psi)**		
		1%	**2%**	**3%**	**4%**	**1%**	**2%**	**3%**	**4%**	**1%**	**2%**	**3%**
1800	**SL**	2.3	11.7	22.3	22.2	1.3	7.7	17.9	28.2	21.5	36.6	63.3
	DL	2.0	10.1	21.6	25.8	0.9	8.3	20.2	32.8	21.5	36.6	63.3
2400	**SL**	2.4	10.4	20.4	28.3	1.3	8.6	20.4	33.4	21.5	36.6	63.3
	DL	2.4	10.4	20.4	28.3	1.5	9.0	20.3	33.8	21.5	36.6	63.3

Table 10: Energy dissipated per cycle of drift of control prototype, retrofitted prototype and retrofitted hollow prototype

Concrete (psi)	**CFRP Layers**	**Energy Dissipated per cycle of Drift (Kip-in)**										
		Control Prototype				**Retrofitted Prototype**				**Retrofitted Hollow Prototype (3400 psi)**		
		1%	**2%**	**3%**	**4%**	**1%**	**2%**	**3%**	**4%**	**1%**	**2%**	**3%**
1800	**SL**	147	749	1,427	1,421	83	493	1,146	1,805	4,644	7,906	13,673
	DL	128	646	1,382	1,651	58	531	1,293	2,099	4,644	7,906	13,673
2400	**SL**	154	666	1,306	1,811	83	550	1,306	2,138	4,644	7,906	13,673
	DL	154	666	1,306	1,811	96	576	1,299	2,163	4,644	7,906	13,673

Table 11: Energy dissipated per cycle of drift/ Net x-sectional area of control prototype, retrofitted prototype and retrofitted hollow prototype

Concrete (psi)	**CFRP Layers**	**Energy Dissipated per cycle of Drift /Net X-Sectional Area (Kip-in/in^2)**										
		Control Prototype				**Retrofitted Prototype**				**Retrofitted Hollow Prototype (3400 psi)**		
		1%	**2%**	**3%**	**4%**	**1%**	**2%**	**3%**	**4%**	**1%**	**2%**	**3%**
1800	**SL**	0.08	0.41	0.79	0.79	0.05	0.27	0.63	1.00	0.36	0.61	1.05
	DL	0.07	0.36	0.76	0.91	0.03	0.29	0.71	1.16	0.36	0.61	1.05
2400	**SL**	0.08	0.37	0.72	1.00	0.05	0.30	0.72	1.18	0.36	0.61	1.05
	DL	0.08	0.37	0.72	1.00	0.05	0.32	0.72	1.20	0.36	0.61	1.05
Net x-sectional Area (in^2)		1,809				1,809				12,971		

5.3.2 Cumulative Energy Dissipated

For comparison of cumulative energy dissipated by control column, retrofitted column and retrofitted hollow column the same procedure described in section 5.3.1 was used to convert the cumulative energy dissipated by the models into prototype cumulative energy and then the cumulative energy dissipated per unit net x-sectional area of control prototype, retrofitted prototype and retrofitted hollow prototype was calculated. From the comparison of cumulative energy dissipation data among the prototypes it was concluded that there is a general trend that the cumulative energy dissipated by the retrofitted hollow prototype is less than the control prototype and retrofitted prototype. The results obtained are summarized in the proceeding tables.

Table 12: Comparison of cumulative energy dissipated

		Cumulative Energy Dissipated (Kip-in)						**Cumulative Energy Dissipated/ Net X-Sectional Area (kip-in/in^2)**		
Concrete (psi)	**CFRP Layers**	**Control Model (1:4)**	**Retrofitted Model (1:4)**	**Retrofitted Hollow Model (3400 psi) (1:6)**	**Control Prototype**	**Retrofitted Prototype**	**Retrofitted Hollow Prototype (3400 psi)**	**Control Prototype**	**Retrofitted Prototype**	**Retrofitted Hollow Prototype (3400 psi)**
1800	**SL**	86	106	187	5,517	6,765	40,465	3.0	3.7	3.1
	DL	86	117	187	5,517	7,494	40,465	3.0	4.1	3.1
2400	**SL**	110	121	187	7,066	7,731	40,465	3.9	4.3	3.1
	DL	110	122	187	7,066	7,789	40,465	3.9	4.3	3.1
Net x-sectional area (in^2)		113	113	360	1,809	1,809	12,971	1,809	1,809	12,971

5.4 Response Modification Factor:

5.4.1 Calculation of R-Factor:

The response modification factor for model hollow bridge column was calculated using Non Lin software. The ductility demand for the model hollow bridge column was 2.2 and the cumulative energy dissipated was 187.34 Kip-in. The values of these two parameters were used as a threshold value while performing the analysis in the NonLin software. It was made sure that the ductility demand and the energy dissipated do not exceeded the threshold values of the model hollow bridge column. If such a case was observed that either ductility demand or the energy dissipated exceeded the threshold values, the peak ground acceleration of the selected earthquake was modified by multiplying it with a suitable factor and the ductility demand and the energy dissipated values were brought within the range of threshold values. The linear and nonlinear forces were calculated and the R-Factor was calculated by dividing linear force by nonlinear force. The ductility demand, linear, nonlinear force and the energy dissipated calculated from various earthquake time histories and the corresponding R-Factors are summarized in the table given below.

Table 13: Response Modification Factor calculated for selected seven earthquake time histories

Time History	**Time History Name**	**% of Time History**	**PGA**	**μ**	**$F_{Non\ Linear}$** (Kips)	**F_{Linear}** (Kips)	**Enegy Non Lin** (Kip-in)	**R_μ**
1	IMPVAL1	94%	0.33	2.17	28.83	50.56	38.59	1.75
2	MEXCIT1	510%	0.51	2.12	28.41	33.46	11.12	1.18
3	LOMA-P1	152%	0.42	2.15	28.69	41.03	17.03	1.43
4	PACOIMA1	38%	0.41	2.18	28.93	42.25	17.81	1.46
5	KERN-1	189%	0.30	2.181	28.93	49.07	55.58	1.70
6	NRIDGE1	69%	0.41	2.192	29.03	34.13	10.45	1.18
7	S.MONICA1	29%	0.26	2.192	29.08	47.53	23.68	1.63
							Average R_μ	**1.48**

5.4.2 Comparison between calculated R-Factor value and AASHTO LRFD 2007 guidelines[1]

The average calculated R-factor value of hollow circular column is 1.48. The R-Factor value for hollow circular column is less than the AASHTO LRFD guidelines specified for Importance category Critical, Essential and Others. Hence the bridge designed on the basis of this R-Factor value will allow more inelastic action and more energy imparted by a large earthquake will be dissipated.

Table 14: Comparison between calculated and specified R-Factor values

Response Modification Factor Values			
Hollow Circular Column	**AASHTO LRFD Values for Single Columns**		
	Critical	Essential	Others
1.48	1.5	2.0	3.0

6 Conclusions and Recommendations:

6.1 Conclusions:

1. The damping ratio of the hollow bridge column for North-South and E-W face was with in the usual damping range of 5% for elastic systems[7].
2. When the hollow column was subjected to unknown damage before retrofitting, the South face was much more damaged and the North face was relatively less damaged. This was the reason that after retrofitting the North face of the hollow column was able to take load up to 17 tons.
3. The energy dissipated per cycle increased with the increase in percentage drift and the energy dissipated in the 2nd cycle was less than the Ist cycle in each drift.
4. The energy dissipated per cycle by the retrofitted hollow column was greater than solid circular column and retrofitted solid circular column.
5. The cumulative energy dissipated by the retrofitted hollow column was less than the solid circular column and retrofitted solid circular column.
6. The stiffness of the column decreased with the increase in percentage drift.
7. The equivalent damping of the column increased with the increase in drift up to 1% and then a decrease in equivalent damping with the increase in drift was observed.

6.2 Recommendations:

1. In quasi-static cyclic testing there is enough time to observe damages and changes as compared to dynamic testing. Therefore quasi-static cyclic testing is recommended when we require time to observe damages to the specimen at different intervals.

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