- Technical Paper -

SHEAR STRENGTHENING OF RC BRIDGE PIERS BY STEEL JACKETING USING NEW CEMENTITIOUS ADHESIVES

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ABSTRACT

This research is an attempt to study the possible application of new inorganic cementitious material as an adhesive for the shear strengthening of RC piers by steel jacketing. A total number of three specimens including one control specimen and two retrofitted specimens were tested under reversed cyclic loading. In the retrofitted specimens, light weight mortar and mortar with mineral admixtures were used to inject between steel jacket and concrete column. Test results show that both the mortars were effective in shear strengthening by providing the ductility factor of retrofitted columns higher than 8.5.

Keywords: reinforced concrete pier, shear strengthening, steel jacketing, mortar

1. INTRODUCTION

Many highway structures have been designed and constructed prior to the implementation of modern seismic design codes. The recent severe earthquakes, such as the 1995 Hyogo-ken Nanbu Earthquake in Japan, exhibited numerous examples of catastrophic shear failure of reinforced concrete (RC) columns. Many bridges that collapsed in the earthquake were designed before the introduction of 1980 seismic resistant design codes [1,2]. Based on investigations different preventive actions were proposed to identify the deficient bridges and to apply suitable strengthening techniques to overcome any unsatisfactory performance [3]. Several bridge piers were subsequently retrofitted while a number of them still need to be strengthened. Out of several retrofitting techniques, steel jacketing is one of the most effective and the commonly implemented one.

While retrofitting RC columns by steel jacketing, non-shrinkage mortar or epoxy resin are injected between the steel jacket and concrete pier [4]. Since the epoxy resin is very expensive, many researchers have studied the application of non-shrinkage cementitious materials [5-8]. While using cementitous materials, by considering the flowability, a wider gap has to be provided between steel jacket and concrete. The use of normal mortar, therefore, leads to an increased weight of the structure, which adds to the dead load to the foundation, and attracts more inertial load in an earthquake. It will also increase an undue pressure on the steel jacket, especially at its bottom portion.

This research focuses on the application of cementitious filling materials and the applicability of light weight cement mortar for the shear strengthening of RC columns by steel jacketing.

2. EXPERIMENTAL PROGRAMS

In order to investigate the influence of cementitious adhesives on the performance of seismic retrofitted columns with steel jackets, three specimens were tested. The first specimen was a control specimen without any retrofitting, while the second and the third specimen were retrofitted by steel jacketing. Table 1 shows the descriptions of the test specimens.

Table 1 Descriptions of test specimens

Sp.	Description	Mortar type
N	Control specimen	-
SJ-1	Retrofitted with steel jacket	Pre-mixed light weight
SJ-2	Retrofitted with steel jacket	Mortar with mineral admixtures

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Fig. 1 shows the dimensions and the reinforcement details of all the tested specimens. Cross-section of the specimen was 300 x 300 mm while the overall height of the column was 1000 mm. The height of the loading point from the column footing joint was 830 mm. 16 D-16 bars were provided as longitudinal reinforcements while no lateral reinforcements were provided in the shear span in order to ensure shear failure of the control specimen. Shear-span-to-depth ratio (a/d ratio) of the specimens was 3.17.

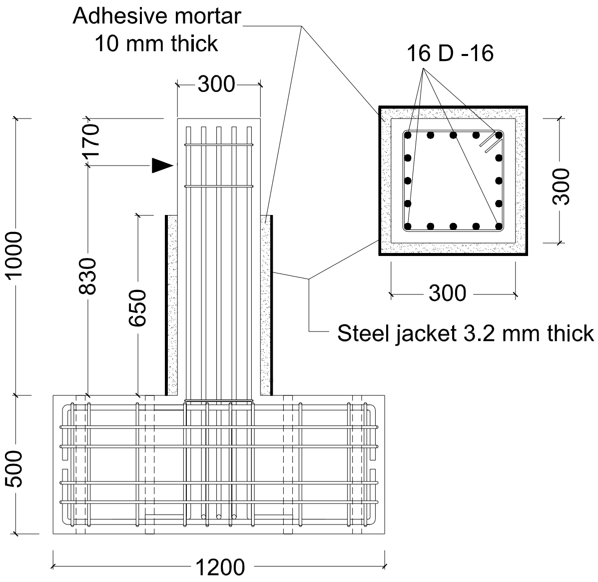


Fig. 1 Details of the test specimen

Steel jacketing for specimens SJ-1 and SJ-2 was done up to the height of 650 mm from the column-footing joint. A gap of 10 mm was provided between steel jacket and concrete column for the injection of cement mortar.

2.1 Material properties

Ready-mixed, normal weight concrete with the maximum size of coarse aggregate of 20mm and an average slump of 150 mm was used. Table 2 shows the 28 day compressive strength of the concrete, yield strength of longitudinal reinforcing bars, and that of steel jacket.

Two types of mortars, namely, pre-mixed light weight type and mortar with mineral admixtures were used in specimens SJ-1 and SJ-2, respectively. The properties of the mortars are as shown in Table 3.

Table 2 Material properties

Sp. ID	fc' (N/mm^2)	Yield strength of longitudinal bars (N/mm^2)	Yield strength of steel jacket (N/mm^2)
N	33	397	-
SJ1	33	397	314
SJ2	33	397	314

2.2 Experimental setup and instrumentation

Fig. 2 shows the experimental setup. The specimen was fixed on strong floor with prestressed rods. Reversed cyclic lateral load was applied at the designated loading point of the column by using an actuator.

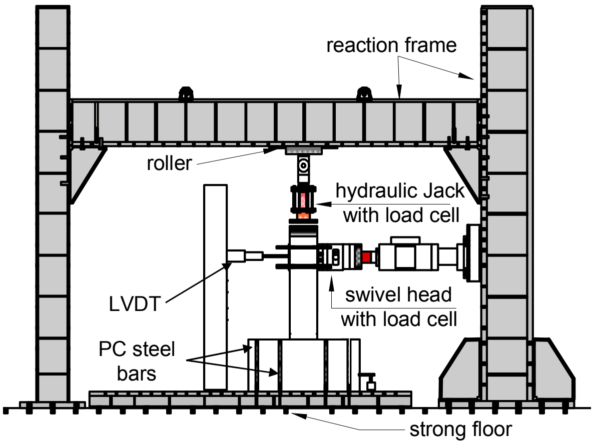


Fig. 2 Experimental setup

Table 3 Properties of mortar

Mortar type	Curing Condition	Compressive strength (N/mm^2)			Splitting tensile strength (N/mm^2)	Modulus of elasticity (N/mm^2)	
		7 days	28 days	54 days	56 days	28 days	56 days
Pre-mixed light weight	20°C in water	9.22	9.51	-	-	4970	-
	Sealed curing at site	10.50	-	13.50	0.96	-	5810
Mortar with mineral admixtures	20°C in water	43.70	55.70	-	-	24200	-
	Sealed curing at site	44.80	-	65.10	3.65	-	25100

A constant axial load of 90kN was applied throughout the experiment in order to maintain the compressive axial stress of 1 N/mm^2. Axial loading jack was designed to move freely with applied lateral load.

Moreover, the longitudinal bars and steel jacket were instrumented by an array of strain gages.

2.3 Loading sequence

Displacement controlled reversed cyclic loading was applied with the loading sequence shown in Fig. 3, which consists of stepwise loading cycles. Displacement amplitude of $\delta_{y,}$ the calculated yield displacement, was applied in the first cycle, which was then followed by the cycles with the displacement amplitudes of $3\delta_y$, $5\delta_y$, $7\delta_y$, $8\delta_y$, $9\delta_y$, $10\delta_y$ and so on until the specimen failed. This loading sequence with minimum number of cycles was used to prevent undesirable low cycle fatigue of longitudinal reinforcements. Specimen is considered to have failed when the load carrying capacity degraded to 80% of its maximum value.

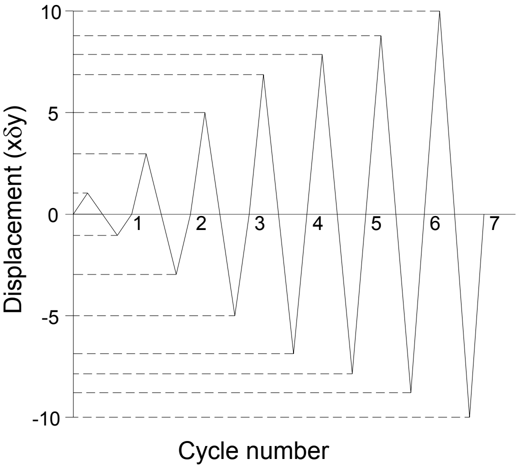


Fig. 3 Loading sequence

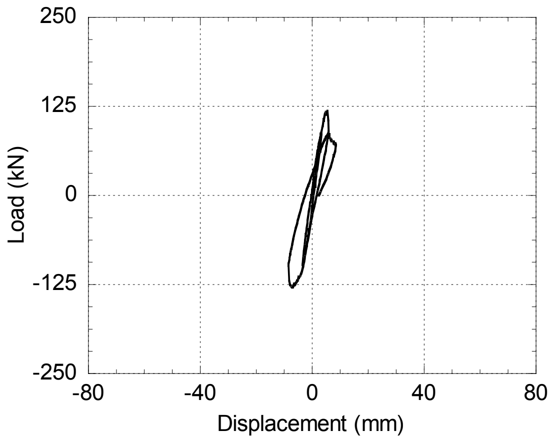
3. EXPERIMENTAL RESULTS

3.1 Load-displacement curves

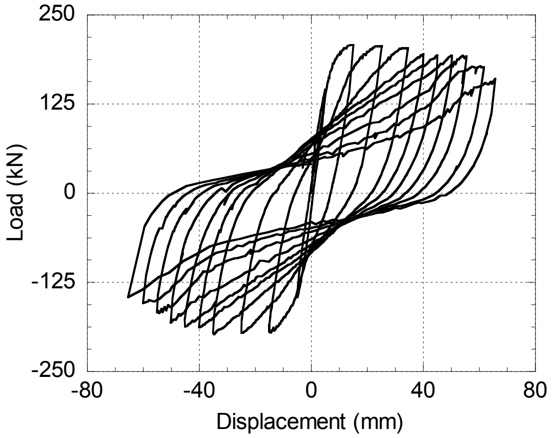
Load-displacement curves of all the specimens obtained from the experiments are shown in Fig. 4.

As expected, specimen N failed in shear prior to the yielding of longitudinal reinforcements. A sudden drop in load carrying capacity occurred after the occurrence of shear crack in clearly noticeable from the load-displacement curve.

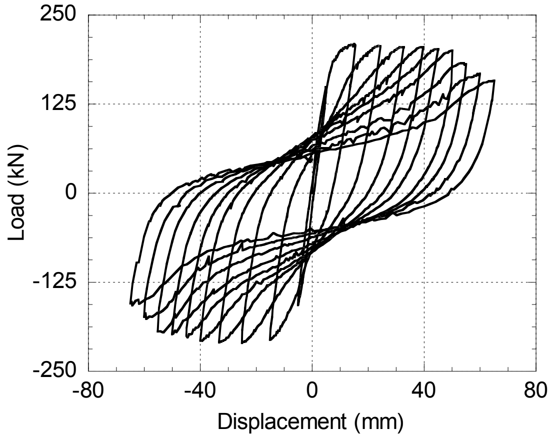
After retrofitting with steel jackets both specimens SJ-1 and SJ-2 showed a ductile flexural behavior. The overall performance of both the shear strengthened specimen in terms of hysteretic behavior and ultimate displacement remained identical.



(a) Specimen N



(b) Specimen SJ-1

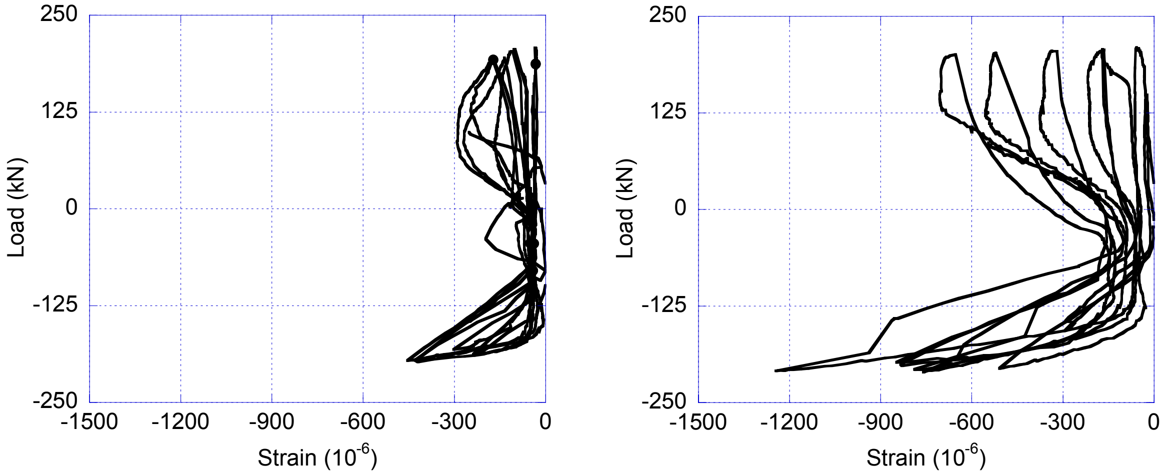


(c) Specimen SJ-2

Fig. 4 Load-displacement curves

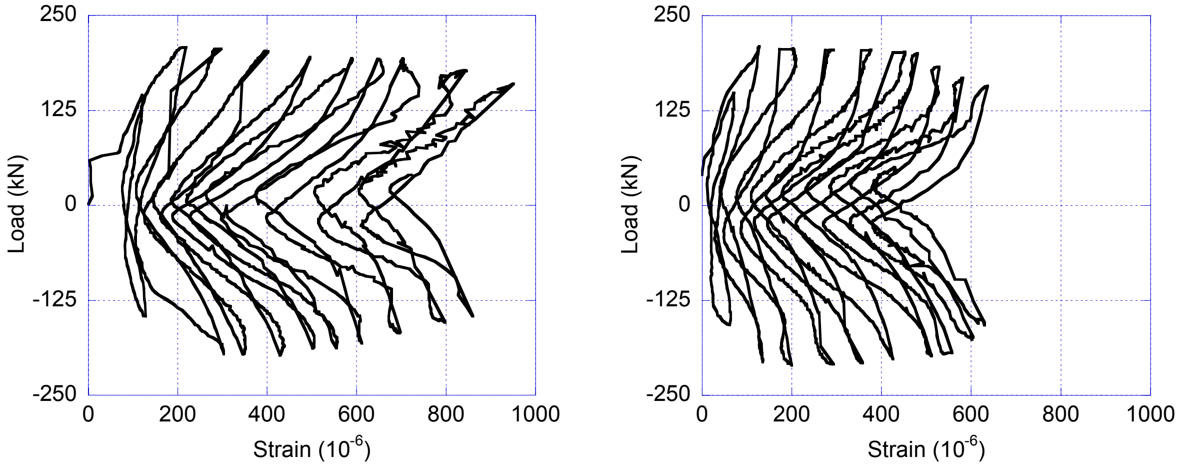
3.2 Strains in the steel jacket

Fig. 5 shows the relationship between load and the vertical compressive strain at the center bottom of the loading face of steel jacket. The results show that the specimen SJ-2 carried much larger compressive strain as compared to that of specimen SJ-1. Since the mortar was weaker in specimen SJ-1, significant upward sliding of the jacket occurred with the load reversals.



(a) Specimen SJ-1 (b) Specimen SJ-2

Fig. 5 Vertical compressive strain on the loading face of steel jacket



(a) Specimen SJ-1 (b) Specimen SJ-2

Fig. 6 Horizontal tensile strain on the front face of steel jacket

Fig. 6 shows the horizontal tensile strain at mid height of the front face of the steel jacket. The results show that the larger tensile strain occurred in specimen SJ-1. The underlying rationale is that in specimen SJ-1 the weaker grout started to crush with larger reversed cycles leading to the widening of shear cracks thus larger tensile strain in the jacket was observed. This was confirmed by the observations of the specimens after loading test by removing the steel jackets.

3.3 Envelope curves

Fig. 7 shows the comparison of the envelope curves of the load-displacement hysterisis of all the tested specimens. Specimen N had much lower load carrying capacity as compared to other retrofitted specimens since it failed in shear prior to the yielding of longitudinal reinforcement. Both the retrofitted specimens SJ-1 and SJ-2 showed similar results. Specimen SJ-2, however, had a slightly higher load carrying capacity owing to the better participation of steel jacket in carrying compressive stress.

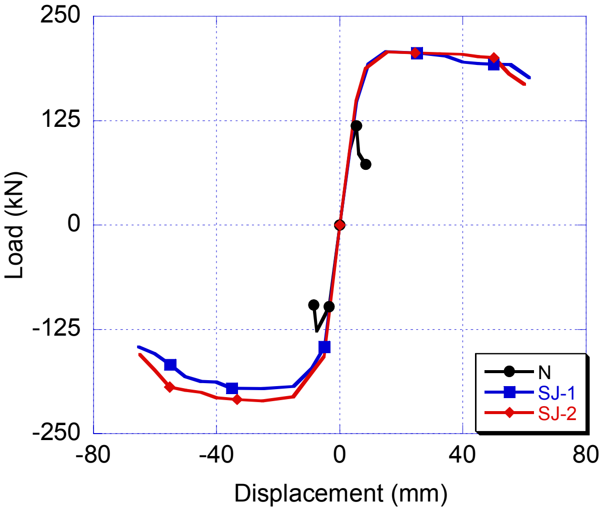
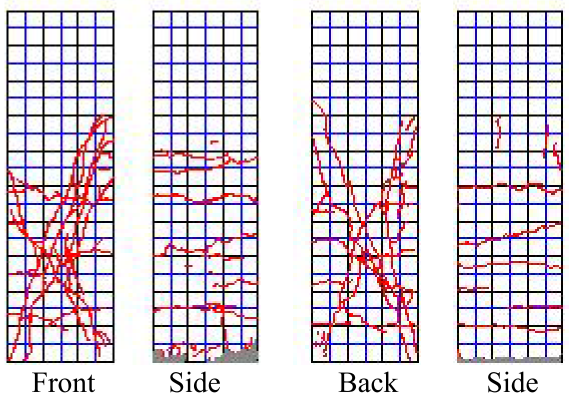


Fig. 7 Envelope curve of the load-displacement hysterisis

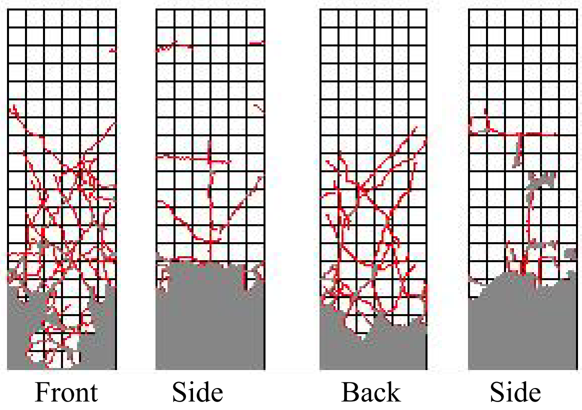
Post peak load carrying capacity of SJ-2 was rather flat while a consistent slight reduction was observed in SJ-1. Gradual crushing of the mortar near column-footing joint is responsible for the gradual reduction of load carrying capacity. Final failure in both the cases was due to crushing of concrete near column-footing joint followed by the buckling of steel jacket.

3.4 Cracking pattern

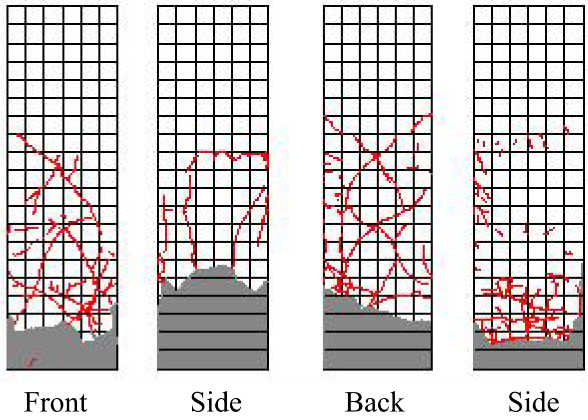
Fig. 8 shows the cracking pattern of all the tested specimens at the ultimate state.



(a) Specimen N



(b) Specimen SJ-1



(c) Specimen SJ-2

Fig. 8 Cracking pattern at ultimate state

Specimen N failed due to the occurrence and subsequent widening of diagonal shear crack. In specimen SJ-1 and SJ-2, fine diagonal cracks were visible in both front and back faces of the column. Due to the presence of steel jacket, shear cracks could not widen and the failure mode of the column changed from shear to flexure. Final failure was due to the combination of buckling of the bottom part of the steel jacket and the crushing and spalling of concrete cover near the column-footing joint.

3.5 Ductility

Ductility factor is defined as the ratio of ultimate displacement to yield displacement. Ultimate displacement is defined as the displacement corresponding to the 20% reduction of lateral load carrying capacity. In order to have an ease in computation and comparison, New Zealand's method, which is considered to provide the most realistic results, is adopted for the computation of yield displacement of tested specimens [9].

Table 4 summarizes the ductility factors computed for specimens SJ-1 and SJ-2 for both push and pull direction of loading. Ductility factor of specimen N could not be computed as it failed in shear prior to the yielding of longitudinal reinforcement. From the computed results, it can be clearly observed that both specimens SJ-1 and SJ-2 showed a good ductile performance with ductility factor of more than 8.5.

Table 4 Ductility of retrofitted specimens

Sp.	Side	P_y^{*} (kN)	δ_y^{**} (mm)	δ_u^{+} (mm)	μ^{++}
SJ-1	Push	173.75	7.19	64.14	8.9
	Pull	157.50	6.69	59.30	8.9
SJ-2	Push	178.13	7.00	61.19	8.7
	Pull	153.13	6.63	61.55	9.3

*Py= Yield load

$^{**}\delta_y$ = Yield displacement

$^{+}\delta_u$= Ultimate displacement

$^{++}\mu = \delta_u/\delta_y$ =ductility factor

3.6 Discussion

In case of specimen SJ-1 with light weight mortar, significant slippage of the jacket occurred against the mortar, as a sound of such slippage was audible during the experiment. In specimen SJ-2 with normal weight mortar, however, there was no such sound.

Rate of degradation of load carrying capacity was slightly different among the retrofitted specimens. In SJ-1 gradual degradation of load carrying capacity was observed after the peak, while the specimen SJ-2 maintained the load carrying capacity until the buckling of steel jacket triggered the spalling of concrete cover. This effect is attributed to the difference in the compressive strength of mortars used.

Since the final failure in both the cases were due to the crushing and spalling of concrete cover followed by the buckling at the bottom of the steel jacket, not much difference was observed in terms of the ultimate displacement.

4. CONCLUSION

An experimental study was carried out to investigate the possible application of pre-mixed light weight mortar and mortar with mineral admixtures for injection into the gap between steel jacket and concrete pier. Based on this experimental study following conclusions can be drawn:

(1) Steel jacket retrofitting by using both pre-mixed light weight mortar and mortar with mineral admixtures are effective in preventing the shear failure and enhancing ductility with the ductility factor of more than 8.5.

(2) In such retrofitting, final failure occurred due to the crushing of concrete near column-footing joint followed by the buckling of steel jacket. The overall behavior of specimens with both pre-mixed light weight mortar and the mortar with mineral admixtures in terms of hysteretic behavior and ultimate displacement, therefore, remained identical.

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