- Technical Paper -

SHEAR STRENGTHENING OF RC BRIDGE PIERS BY STEEL JACKETING WITH EXPANSIVE CEMENT MORTAR AS ADHESIVE

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ABSTRACT

This paper presents the experimental investigation on the application of expansive cement mortar between concrete and steel jacket for seismic retrofitting and repair of RC piers. A total number of three RC columns including a shear critical column, a retrofitted column and a repaired column were tested under reversed cyclic loading. The test results showed that the use of expansive cement mortar for steel jacketing of rectangular columns provides additional confinement to the column concrete enhancing greatly the seismic performance of the column in terms of shear strength and ductility.

Keywords: steel jacket, expansive cement mortar, concrete strength, concrete confinement

1. INTRODUCTION

A number of retrofitting techniques for reinforced concrete bridge piers have been developed and verified experimentally in the past few decades [1-4]. These techniques have been essentially to enhance the seismic performance of these structures in shear. Steel jacketing has been one of the most popular methods for seismic retrofitting of RC columns. It is more popular for circular columns, and for rectangular columns the use of elliptical shaped steel jackets has been recommended [5]. However, in Japan, rectangular piers are often adopted and use of elliptical shaped steel jackets causes difficulty in urban freeways due to limitation of space [6]. Hence in most cases rectangular steel jacketing is adopted and additional arrangements are required to obtain satisfactory results such as lateral ring beam at the bottom of steel jacket [7, 8].

The steel jackets are attached to the RC columns by injecting non-shrinkage mortar or epoxy resin as adhesive [6]. However epoxy resins are quite expensive and the non-shrinkage mortar does not guarantee effective confinement of concrete of the jacketed rectangular RC columns unless properly stiffened.

This research presents the possible application of inorganic expansive cementitious material that can be used as an alternative adhesive material for steel jacketing. The aim is to ensure additional confinement of the column concrete due to chemical prestress generated by expansive mortar thus improving greatly the seismic performance of retrofitted and repaired columns in shear and ductility.

2. EXPERIMENTAL PROGRAM

To investigate the seismic performance of rectangular RC columns with steel jackets using expansive cement mortar as adhesive, three specimens were tested under reversed cyclic loading. The descriptions of these specimens are given in Table 1. The first one was the control specimen without any retrofitting. The second specimen was as built column retrofitted with rectangular steel jackets using expansive cement mortar as adhesive. The concept is to utilize the additional confinement of the column concrete due to expansive cement mortar. The third specimen was severely damaged column with brittle shear failure and a large diagonal crack. This column was repaired with steel jacket using expansive cement mortar for filling the cracks and also as an adhesive between the jacket and column. Along with additional confinement, the aim of using expansive cement mortar for repair is to fill up the crack firmly which could hardly be achieved using conventional cement mortar. The test result of

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these three specimens were used to present the possible applications of steel jacketing with expansive cement mortar as adhesive for retrofit and repair technology.

Table 1 Descriptions of test specimens

Sp. ID	Description
N	Control Specimen
SJ3	Retrofitted with steel jacket
SJ4	Specimen N repaired with steel jacket

Fig. 1 shows the dimensions and other details of the tested specimens. The cross-section of the specimen was 300 × 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. The shear-span-to-depth ratio (a/d) of the specimens was 3.17. 16 D-16 bars were provided as longitudinal reinforcements while no lateral reinforcements were provided in the shear span to ensure shear failure in the control specimen. The other two columns were jacketed to a height of 650 mm from the column-footing joint with 3.2 mm thick steel jacket. The expansive cement mortar of 30 mm thickness was used as the adhesive material for steel jacket. A gap of 50 mm was provided between steel jacket and footing to prevent excessive enhancement of flexural capacity of column [5].

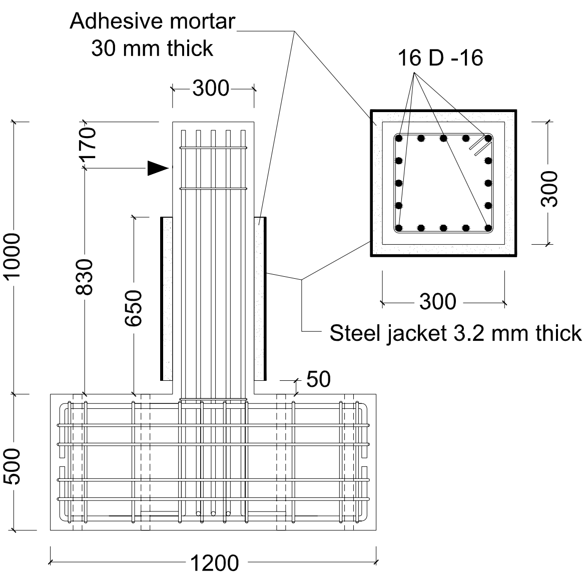


Fig. 1 Details of test specimen

2.1 Materials

(1) Concrete, reinforcing bars and steel jacket

Ready-mixed, normal weight concrete with the maximum coarse aggregate size of 20 mm and average slump of 150 mm was used.

Table 2 shows compressive strength of the sampled concrete cylinders on the day of testing, yield strength of longitudinal reinforcing bars and that of steel jacket.

Table 2 Material properties

Sp. ID	f_c' (MPa)	Yield strength of longitudinal reinforcing bars (MPa)	Yield strength of steel jacket (MPa)
N	49.1	397	-
SJ3	47.0	397	314
SJ4	49.1	397	314

(2) Expansive cement mortar

To determine the effect of expansive cementitious adhesives for steel jacketing, its restrained expansion properties were first studied based on the JIS specification “Standard test method for restrained expansion of expansive cement mortar” [9]. A total number of five mortar moulds were tested. The cross section of all the moulds was 100 × 100 mm while their inner length was 360 mm. The expansive property of the mortar was recorded in terms of strain of the restraining rod of 6 mm diameter which was at axial center of the mould. Two LVDTs were placed on restraining plates on either side of the mould to record the overall elongation of the restraining rod. Fig. 2 shows the moulds used for placing the mould.

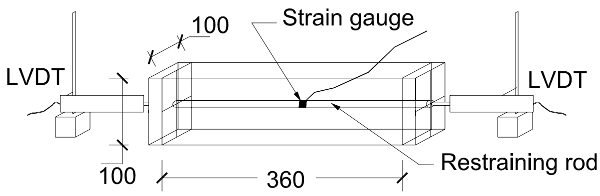


Fig. 2 Details of mould

The mortar was mixed with water cement ratio of 0.4. The moulds were cast with different amounts of expansive cement admixture of Type A to determine the expansive properties of mortar. A fixed quantity of non-shrinkage cement admixture of Type B was also added to prevent shrinkage. After placing the mortar in the moulds, they were wrapped with plastic sheets and kept in the same physical conditions as the steel jacketed specimens would be subjected to.

Table 3 shows the mix proportions of the test specimens and the compressive strength at 7 days.

Table 3 Mix proportion of mortar specimens and their compressive strength

Sp. ID.	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Expansive cement admixture of Type A (kg/m^3)	Non-shrinkage admixture of Type B (kg/m^3)	Average compressive strength (MPa)
SP1	862	942	345	0	80	47.7
SP2	862	942	345	15	80	50.8
SP3	862	942	345	20	80	42.6
SP4	862	942	345	25	80	54.7
SP5	862	942	345	30	80	55.5

The strain on the restraining rod and the corresponding elongation due to expansive cement were recorded at an interval of 10 minutes for 24 days. Fig. 3 shows the strain developed on the restraining rod due to expansion of mortar. These curves clearly show the fluctuations in strain of the rod with daily temperature variations.

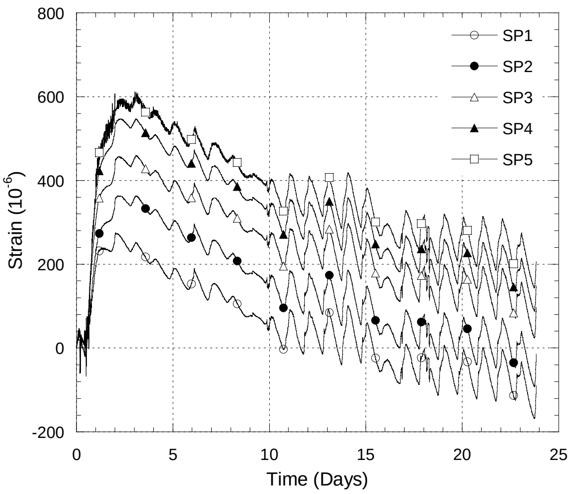


Fig. 3 Strain in restraining rod

As the mortar mix SP1 does not contain any expansive cement admixture, it is considered as reference to determine the actual property of expansive cement admixture and to standardize it. Hence, the strain for mortar mix SP1 was deducted from the strain in other specimens. This in turn also nullifies the temperature effects on the mortar mix and only the property of expansive cement admixture is highlighted. This can be expressed by Eq. 1.

$$\varepsilon_S = \varepsilon_{SP(X)} - \varepsilon_{SP1} \quad (1)$$

where,

ε_S : Standardized strain

$\varepsilon_{SP(X)}$: Recorded strain on SP 2, 3, 4 or 5

ε_{SP1} : Recorded strain on SP1

Fig 4 shows the standardized strain developed in the restraining rod due to expansive mortar. The obtained results clearly demonstrate that using higher amount of expansive cement admixture results in greater expansion of cement mortar. Based on this experiment, the mortar mix of SP5 was selected as an alternative material to epoxy resin for steel jacketing of rectangular column.

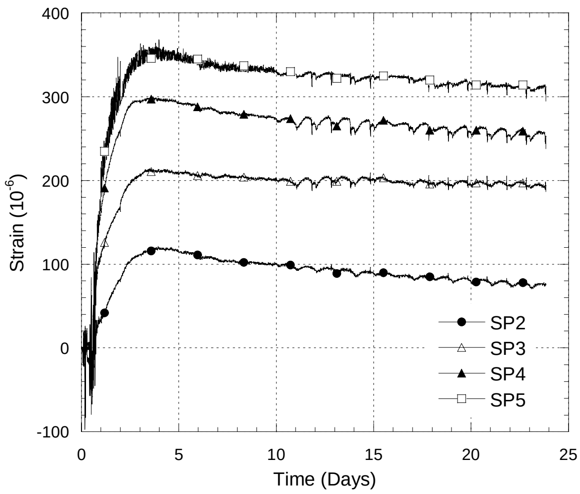


Fig. 4 Standardized strain in restraining rod

2.2 Experimental Setup and Instrumentation

Fig. 5 shows the experimental setup for the test.

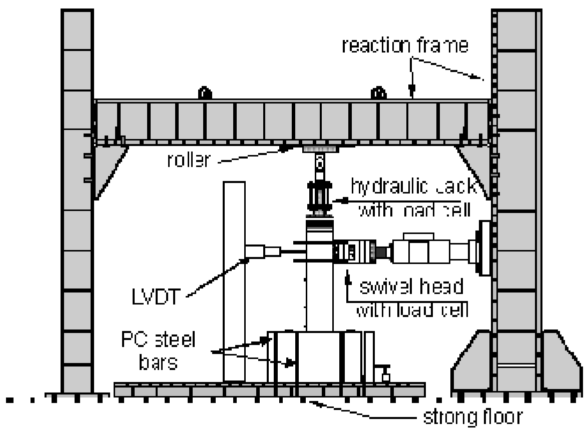


Fig. 5 Experimental setup

Prestressed rods were used to fix the test specimen on strong floor. Axial load was applied to the top of the column and was maintained at a constant level of 90 kN during testing so as to maintain the compressive axial stress of 1 MPa. Reversed cyclic load was then applied at the predefined loading height using an actuator operated under displacement control. The behavior of the columns was monitored during the test by several strain gages installed on the longitudinal bars and steel jackets.

2.3 Loading Program

Displacement controlled stepwise reversed cyclic loading as shown in Fig. 6 was applied to the columns. The displacement amplitude of δ_y, $3\delta_y$, $5\delta_y$, $7\delta_y$, $8\delta_y$, $9\delta_y$, $10\delta_y$ and so on was applied until failure, where δ_y is the calculated yield displacement (5 mm). This loading sequence with minimal number of load reversals was used to prevent the undesirable premature low cycle fatigue of longitudinal reinforcements. The specimen is considered to have failed when its load carrying capacity degraded to 80% of the peak value and the corresponding displacement is regarded as ultimate displacement.

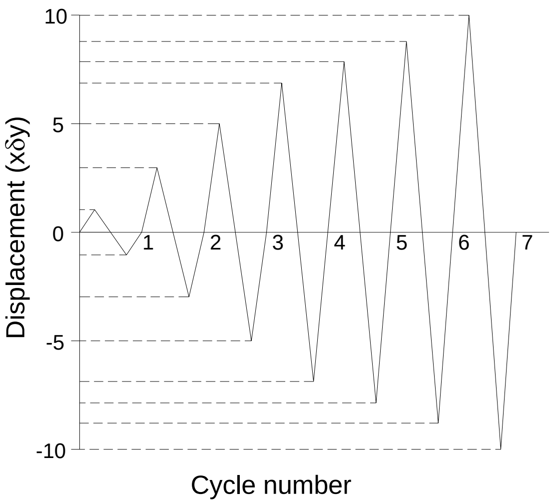


Fig. 6 Loading sequence

3. RESULTS AND DISCUSSION

3.1 Load-Displacement Curve

Fig. 7 shows the load-displacement curve obtained from the test of the control specimen N. As expected, premature shear failure was observed even before the yielding of longitudinal reinforcements. The result of this specimen was taken as a reference to evaluate the performance of the retrofitted and repaired column specimens.

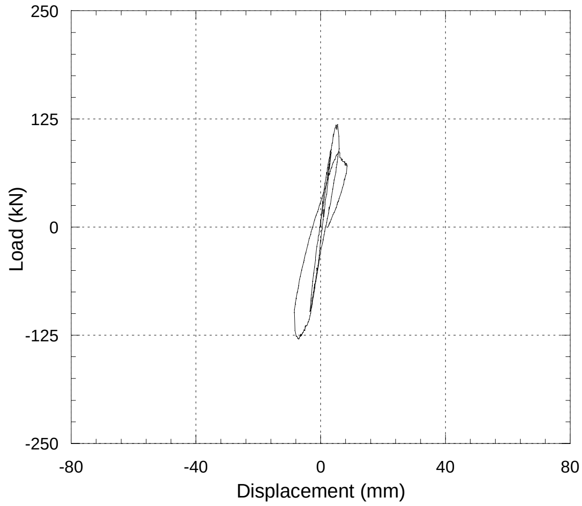


Fig. 7 Load-displacement curve for the control specimen

(1) Retrofitted specimen SJ-3

The specimen SJ-3 showed ductile flexural behavior with appreciable increase in lateral load carrying capacity compared to control specimen. Ductility factor of around 7.5 was obtained and the specimen eventually failed due to yielding of longitudinal bars and crushing of concrete near the column-footing joint. The crushing of column concrete near the column-footing joint was accelerated by the lateral buckling of the bottommost portion of steel jacket on either loading faces. Fig. 8 shows the load-displacement curve for this specimen.

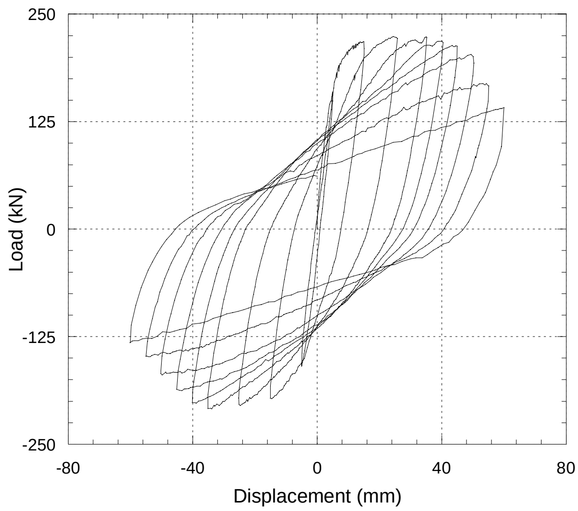


Fig. 8 Load-displacement curve for the specimen SJ-3

(2) Repaired specimen SJ-4

Fig. 9 shows the extent of damage to the specimen SJ-4 before repair.

Fig. 9 Specimen SJ-4 before and after repair

Though this specimen was heavily damaged in shear, after repair it showed satisfactory seismic behavior. Fig. 10 presents the load-displacement curve for this specimen. Ductility factor of around 5.7 was obtained. The final failure mode for this specimen was also due to yielding of longitudinal bars and crushing of concrete near the column-footing joint followed by the lateral buckling of steel jacket.

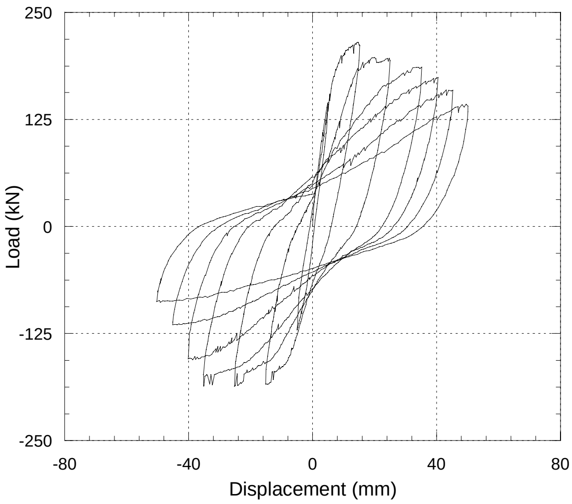
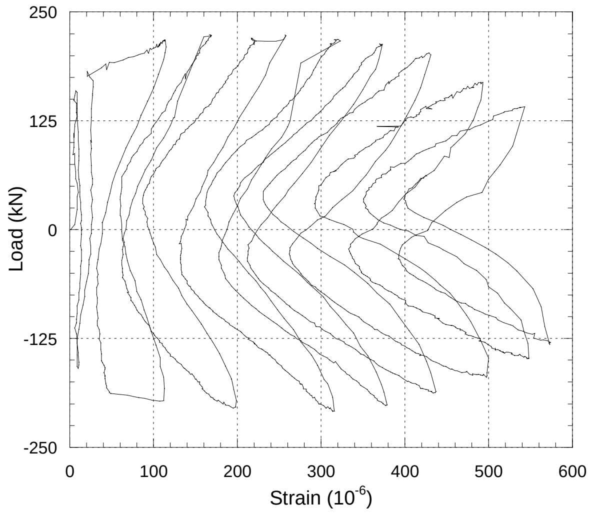


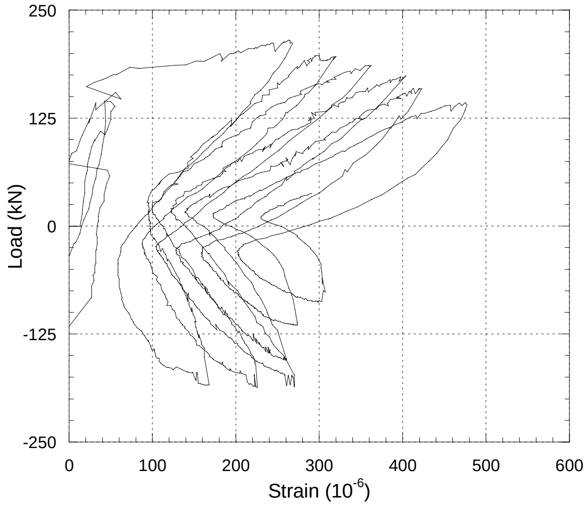
Fig. 10 Load-displacement curve for the specimen SJ-4

3.2 Strain Profile for Steel Jacket

Fig. 11 presents horizontal tensile strain at the mid height of the front face of the steel jacket for the specimens SJ-3 and SJ-4 respectively. The strains presented here do not incorporate the strain developed by chemical prestress of expansive cement mortar. These strains arise due to bearing of column concrete against the steel jacket in the process of development of diagonal crack during reversed cyclic loading.



(a) Specimen SJ-3



(b) Specimen SJ-4

Fig. 11 Horizontal tension strain

The strain profile shows nearly uniform increase in strain with each loading cycle for the retrofitted specimen SJ-3. However, for the specimen SJ-4 there is a sudden increase of strain on push side while attaining peak load. This can be attributed to the sudden opening of shear crack in specimen SJ-4 as the column repaired by the mortar lacks aggregate interlocking action compared to the retrofitted specimen.

3.3 Envelope Curves

The envelopes of the load-displacement hysteresis curves for all specimens are compared as shown in Fig. 12. The specimen SJ-3 had much higher load carrying capacity compared to control specimen N. The seismic performance of the heavily damaged specimen SJ-4 was also found to be satisfactory after repair. The stiffness of the repaired specimen SJ-4 also matched with that of specimen SJ-3 signifying the effectiveness of expansive cement mortar for the confinement of column concrete. Finally, in both the jacketed specimens SJ-3 and SJ-4, crushing of concrete near the column-footing joint triggered by the lateral buckling of steel jacket in that region caused the gradual reduction of lateral load carrying capacity.

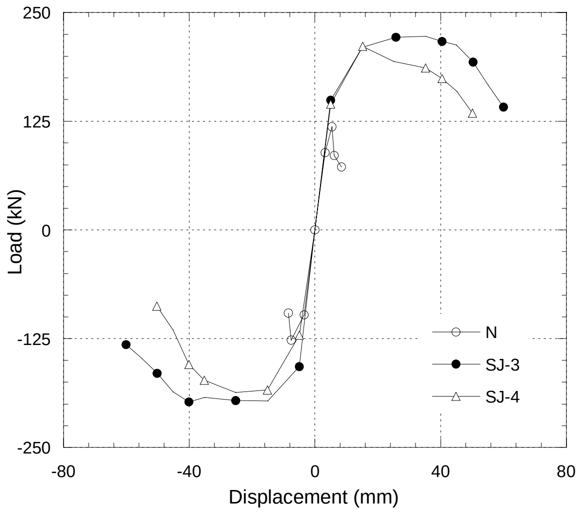


Fig. 12 Hysteresis envelope curves for the tested specimens

4. CONCLUSION

Reversed cyclic loading tests were carried out on three rectangular column specimens. The first specimen was as-built control specimen and the second one was retrofitted with steel jacket. The third specimen was heavily damaged column repaired with steel jackets. Both second and third specimens used expansive cement mortar as adhesive.

Based on the experimental results, following conclusions can be drawn:

(1) The test of expansive cement mortar showed that it can expand under restrained conditions. This property of it can be used for retrofit and repair of RC columns using rectangular steel jackets.
(2) The test results on retrofitted specimen showed that steel jacket retrofitting of rectangular columns using expansive cement mortar is effective in preventing shear failure and enhancing ductility.
(3) Furthermore, the test on heavily damaged column also showed satisfactory seismic behavior. This demonstrates the possible future application of expansive cement mortar in repair and rehabilitation of damaged RC columns.

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