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A New Steel Jacketing Method for Concrete Cylinders and Comparison of the Results with a Constitutive Model

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Abstract

This paper introduces a new steel jacketing method for reinforced concrete columns with lap splice and evaluates its performance by a series of axial tests of concrete cylinders. At first, 45 concrete cylinders were fabricated with varying the design compressive strengths of 21, 27 and 35 MPa and, then, the part of them was jacketed with two-split-steel jackets under lateral confining pressure. The parameters in the first test were the steel jacket's thickness and the existence of adhesive between steel and concrete surface. In the second test, whole steel jackets were used to wrap cylinders with lateral pressure. Also, a double-layer jacket consisted of two steel plates was introduced; a cylinder was jacketed by two steel plates one after another. The effect of the new method was verified through comparing the results of the compressive tests for plain and jacketed cylinders. The steel jacket built following the new method showed good results of increasing the compressive strength and ductility of the jacketed cylinders with respect to the plain cylinders. The thicker steel jackets showed the more increased compressive strength, and the ductility at failure depended on the welding quality on steel jackets. The adhesive between steel and concrete surface reduced the confining effect of the steel jackets. The whole jacket showed more ductile behavior than the two-split jackets. The double-layered jackets were estimated to possess an equal performance to that of a single steel jacket having the same thickness of the double-layered jacket. Finally, the experimental results were compared with the constitutive model of steel-jacketed concrete; which showed a good agreement between the experimental results and the models.

Keywords : *Steel Jacket, RC Columns, Grouting, Seismic Retrofit, External pressure*

1. Introduction

Recent earthquakes in urban areas, such as 1989 Loma Prieta and 1994 Northride in the United States, and 1995 Kobe in Japan, have induced damages to many reinforced concrete columns in bridges and buildings; which indicates that the reinforce concrete columns built before 1970s do not possess the adequate strength and deformation capacity and retrofits for them are required (Buckle, 1994; Priestly, 1988). Investigation of bridge failures after the above earthquakes indicated that the most critical causes of the failures were inadequate lateral reinforcement and insufficient lap length of bars. A lot of existing bridges were designed and constructed along with smaller seismic loads compared to that from the current design codes; which can lead to major damages or collapses of bridges due to an expected earthquake. Therefore, seismic retrofit techniques have been developed for the substandard RC columns.

Steel jackets were used in retrofitting of reinforced columns and were proved to be efficient to increase the strength and ductility of the columns with providing additional confinement and shear resistance (Park and Paulay, 1975). However, the existing steel jacketing has a critical shortcoming; the grouting is needed to fill up the gap between concrete surface and steel jacket. The grouted section is larger than the as-built one; which makes a sectional discontinuity in columns. The application of fiber-reinforced polymer (FRP) as a jacket for vulnerable columns to seismic load has provided several benefits compared to steel jackets: (1) increase in installation speed, (2) reduce in maintenance cost, (3) ease of handling, and (4) high strength-to-weight ratio. The effectiveness of the

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glass or carbon FRP jackets was demonstrated by many experimental tests (Seible et al., 1997; Karbhari and Gao, 1997; Mirmiran et al., 1998)). However, the FRP jacketing system has the potential of falling off due to the use of epoxy to paste the FRP sheets on RC columns. Recently, advanced jacketing methods were introduced to increase the performance of the jackets. Susantha et al. (2008) introduced a precompressing method on concrete in a circular steel tube and improved its performance. Xiao and Wu (2003) used partially stiffened steel jackets to retrofit RC columns to enhance strength and to improve ductility of concrete. Mortazavi et al. (2003) used pre-tension FRPs to strengthen RC columns. They used a prefabricated circular FRP tube to place a concrete cylinder and, then, put expansive grout between them to induce pre-tension on the FRP jacket.

This study introduced a new steel jacketing method to retrofit RC columns without grouting and estimated its performance through the compressive tests of concrete cylinders. The new method used mechanical external pressure on steel plates around RC columns to attach the steel plates on concrete surface. A suite of 45 concrete cylinders and another suite of 15 cylinders were fabricated to estimate the performance the new steel jacketing method. Finally, the experimental results were compared with the constitutive model of steel jacketed concrete to verify the proposed jacketing method.

2. 45 Concrete Cylinders and Two Split Steel Jackets

The first set of the tests has three parameters of the design strength of concrete cylinders, the thickness of steel jackets, and the adhesive on concrete surface. 45 concrete cylinders of 150 mm × 300 mm ($\phi \times L$) were fabricated with varying the design strength of 21, 27, and 35 MPa; there are 15 cylinders for each type of cylinders, respectively. In this test, two split steel jackets and two vertical strip bands were used to confine a cylinder as shown in Fig. 1. The thicknesses of the steel jackets are 1.0 and 1.5 mm. The dimension of a steel jacket is 230 mm × 290 mm (B × H). The height of the steel jacket is less than that of concrete cylinders, which guaranties that no compressive force is transferred to the steel jackets. The vertical strip bands are used for welding connection of the two split jackets and their dimension is 25 mm × 290 mm (B × H). The last parameter is the adhesive located between steel jackets and concrete surface. The adhesive is assumed to be helpful to paste a steel jacket on concrete surface. The used adhesive was Polyurethane film of 0.05 mm thickness that is melted by heating for 5 minutes with 120°C.

There are four kinds of jacketing schemes such as; Case-1) 1.0 mm steel plate with the adhesive, Case-2) 1.0 mm steel plate without the adhesive, Case-3) 1.5 mm steel plate with the adhesive, and Case-4) 1.5 mm steel plate without the adhesive. The 36 jacketed cylinders are prepared following the above plan. The jacketing procedure is shown in Fig. 2. At first, wrap the adhesive film around a cylinder and, then, attach two split steel jackets on the cylinder; the wrapping of the film is not required for the cylinders jacketed by steel plates alone (in such Case-2 and Case-4). The next step is to attach two vertical strips aside the two split jackets. Three clamps and two steel bands are used to induce the lateral pressure on the steel jackets; this process makes the steel jackets contact the concrete surface tightly. The two split jackets and the vertical strips are welded by TIG welding (Tungsten Inert-Gas Arc welding) under the lateral pressure; the TIG welding is generally used for thin steel or stainless steel plates. In this process, the lateral pressure induced by the clamps is preserved on the steel jackets. After the welding, the jacketed cylinders are heated by a heating jacket with 200°C for 20 minutes. This process is only for the jackets with the adhesive film.

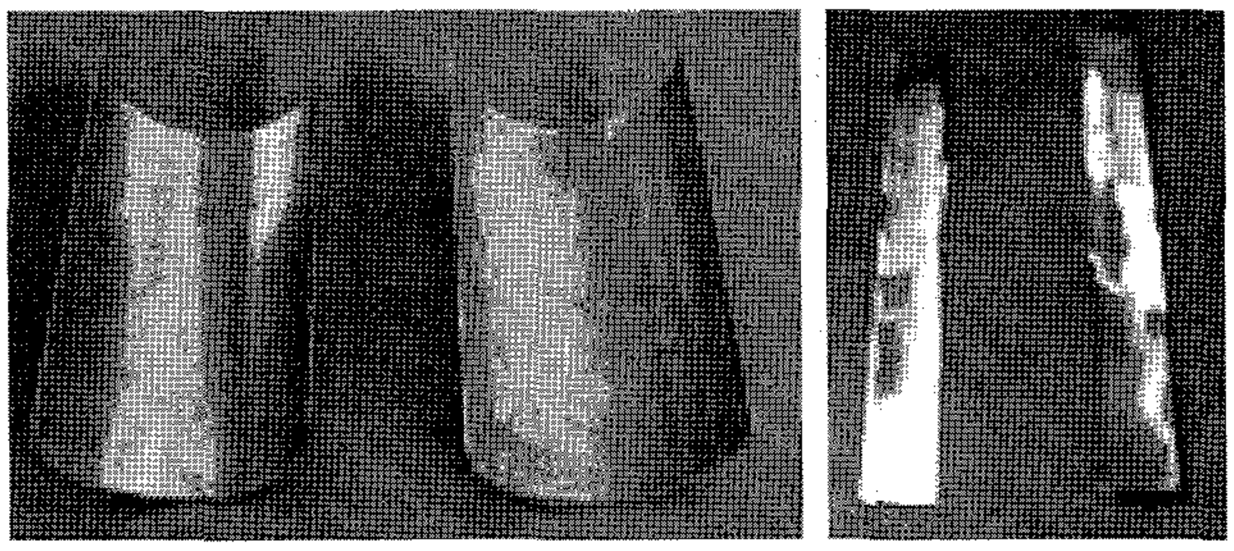


Fig. 1 Two split steel jackets and strip bands

The clamp to introduce lateral pressure on steel jackets has two horse's hoops at the tip as shown in Figure 3(a). The hoop has 5 mm and 300 mm of the thickness and the inside length, respectively, and the inside radius is 150 mm. Thus, the hoops can contact tightly to steel jackets. A shape memory alloy bar shown in Fig. 3(b) was used to measure the tightening force of the clamp as shown in Fig. 3(c). The alloy compounds of Ni and Ti and its Young's modulus is much less than that of steel (DesRoches and Delemont, 2002). The dimension of the bar is 30.0 mm × 25.4 mm (L × D) and the Young's modulus is 63 GPa that is estimated from the stress-strain curve in Fig. 3(d). Three strain gages as shown in Fig. 3(b) were used to measure the strains. When the bolt is tightened strongly by a man, the average measured strain is 479.2×10^{-6}. Thus, the tightening force by the clamp is estimated as 15 kN and the average pressure under the hoops is 5 MPa. The pressure of 5 MPa can be applied on steel jackets directly

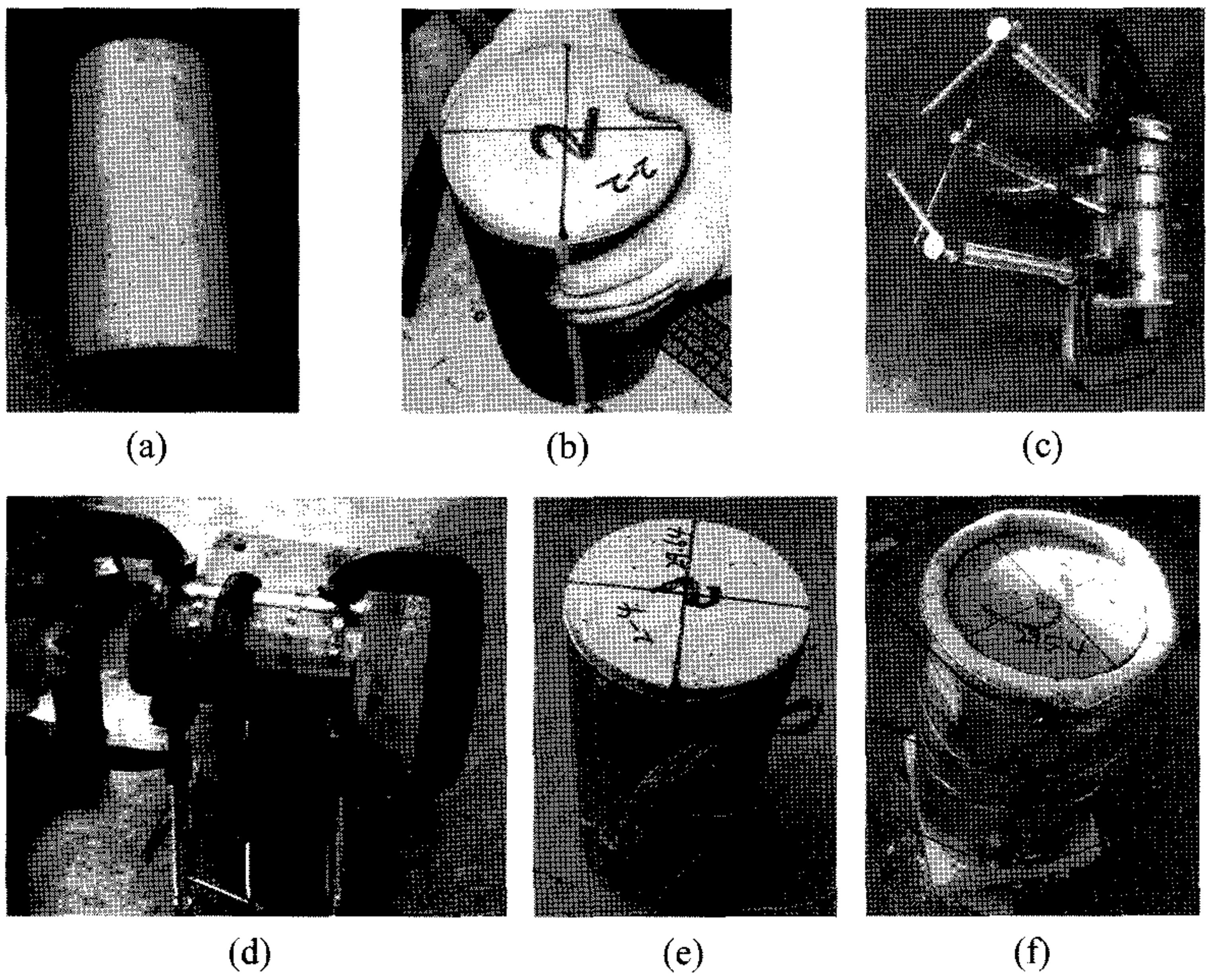


Fig. 2 Procedure to confine a concrete cylinder by two split jackets; (a) wrap the adhesive film; (b) attach the two split jackets on a cylinder; (c) introduce external pressure by clamps; (d) weld the jackets; (e) the completed jacketed cylinder; (f) heat by a heating jacket.

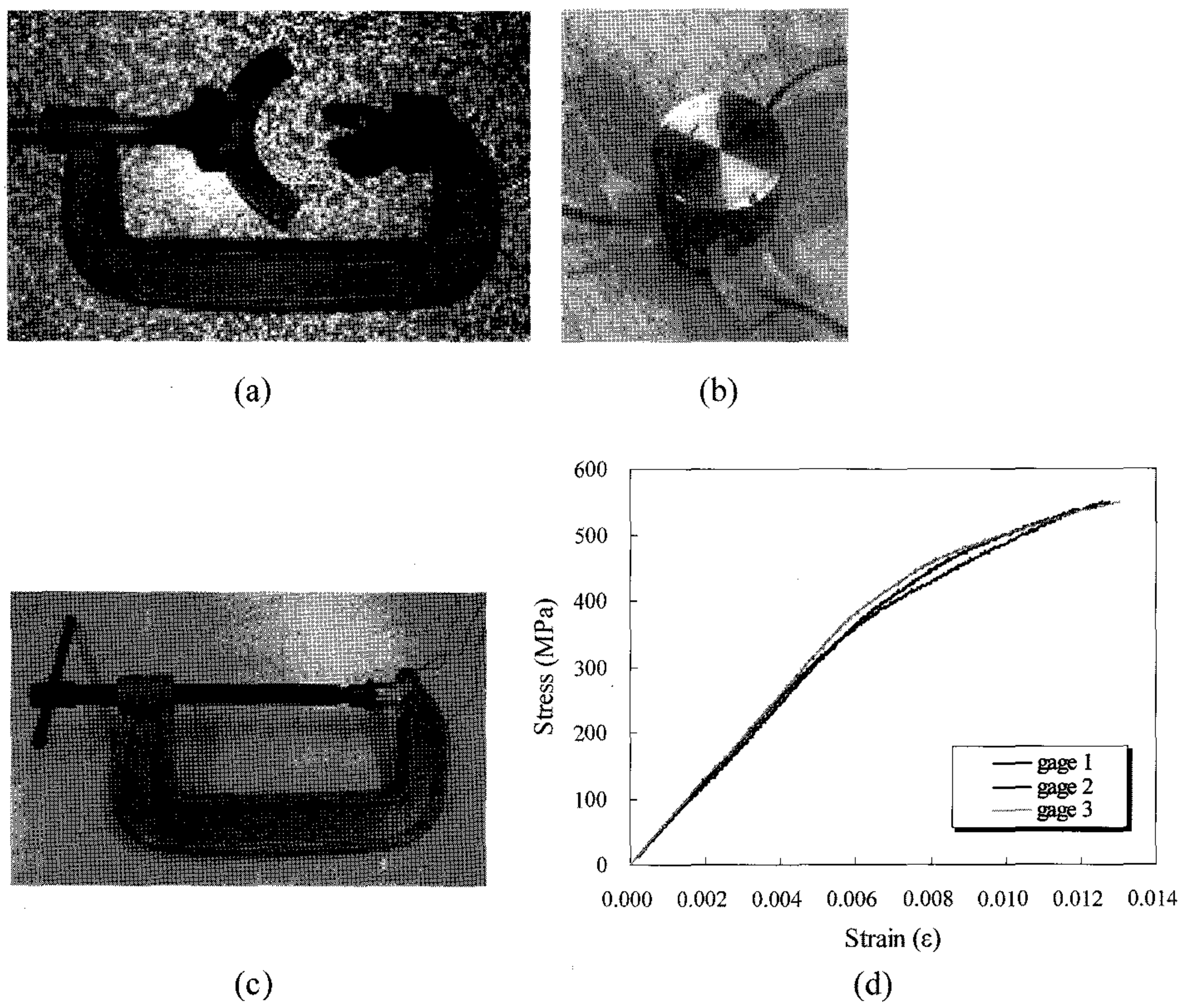
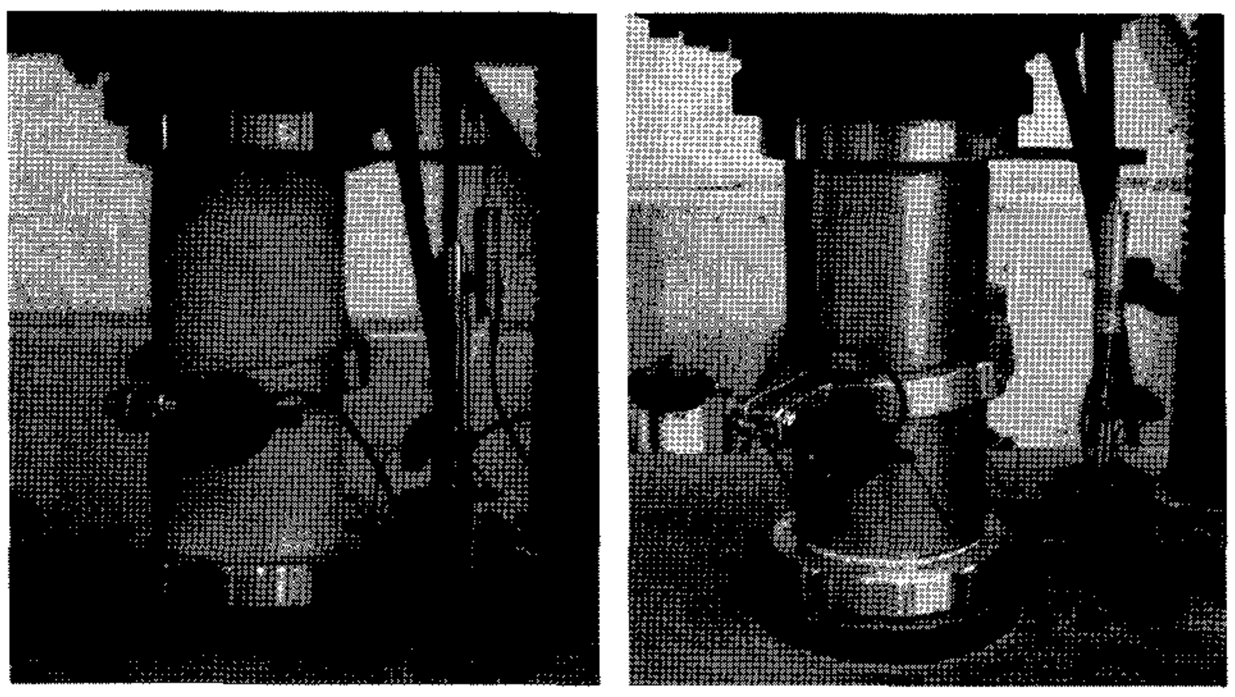


Fig. 3 Measuring the clamping force; (a) hoops in a clamp; (b) shape memory alloy bar used to measure the clamping force; (c) view of measuring clamping force; (d) measured stress-strain curves.

under the clamp. However, the area between the clamps is softly pressed relatively. The used steel jackets are mild steel with the yielding stress of 217 MPa and the fracture strain of 207.6×10^{-3}.



(a) Plain (b) Jacketed

Fig. 4 View of compressive tests for plain and jacketed cylinder

3. Compressive Tests And Results: Part I

A series of compressive tests for three types of plain and jacketed cylinders was performed using a UTM of 2000 kN. A compresometer is feasible to measure the axial deformation of plain cylinders but not applicable for jacketed cylinders. Thus, a displacement transducer located between two rigid plates is used to measure the axial deformation of compressed cylinders as shown in Fig. 4. In the case, a small preload less than 10 kN was required to guarantee a perfect contact between the rigid plates and the concrete surfaces. The axial strains of cylinders are calculated from the axial deformation divided by the original length of the cylinders.

Fig. 5 shows the stress-strain curves of plain and jacketed cylinders of three types of concrete. The averaged peak strengths of 21, 27, and 35 MPa concrete are 33.4, 39.5, and 44.8 MPa, respectively. Also, the corresponding strain to the peak strength is approximately 0.002 as shown in Fig. 5(a); that is corresponding to previous observations (Chen, 2007). As shown in Figs. 5(b)-(d), the proposed steel jacketing method can increase the strength and the ductility of the confined concrete.

Fig. 6(a) shows the peak strengths of plain and jacketed cylinders. Confinement effectiveness is expressed as the ratio of the peak strength of confined concrete to that of plain concrete. Both types of jackets, steel jackets alone and steel jackets plus adhesive, increased the peak strengths of cylinders. However, the adhesive used to stick the steel jackets on concrete surface induces a negative effect on increasing the peak strength; this effect is observed on the jackets of 1.0 and 1.5 mm thickness. The 1.0 mm jackets with the adhesive increase the strengths of 21, 27, and 35 MPa cylinders by 13.0, 8.0, and 7.6%, respectively. The increments of 1.0 mm jacket alone are 36.3, 23.3, and 26.7%, respectively. Thus, the adhesive reduces the increments by 13 to 23% for the 1.0 mm jack-

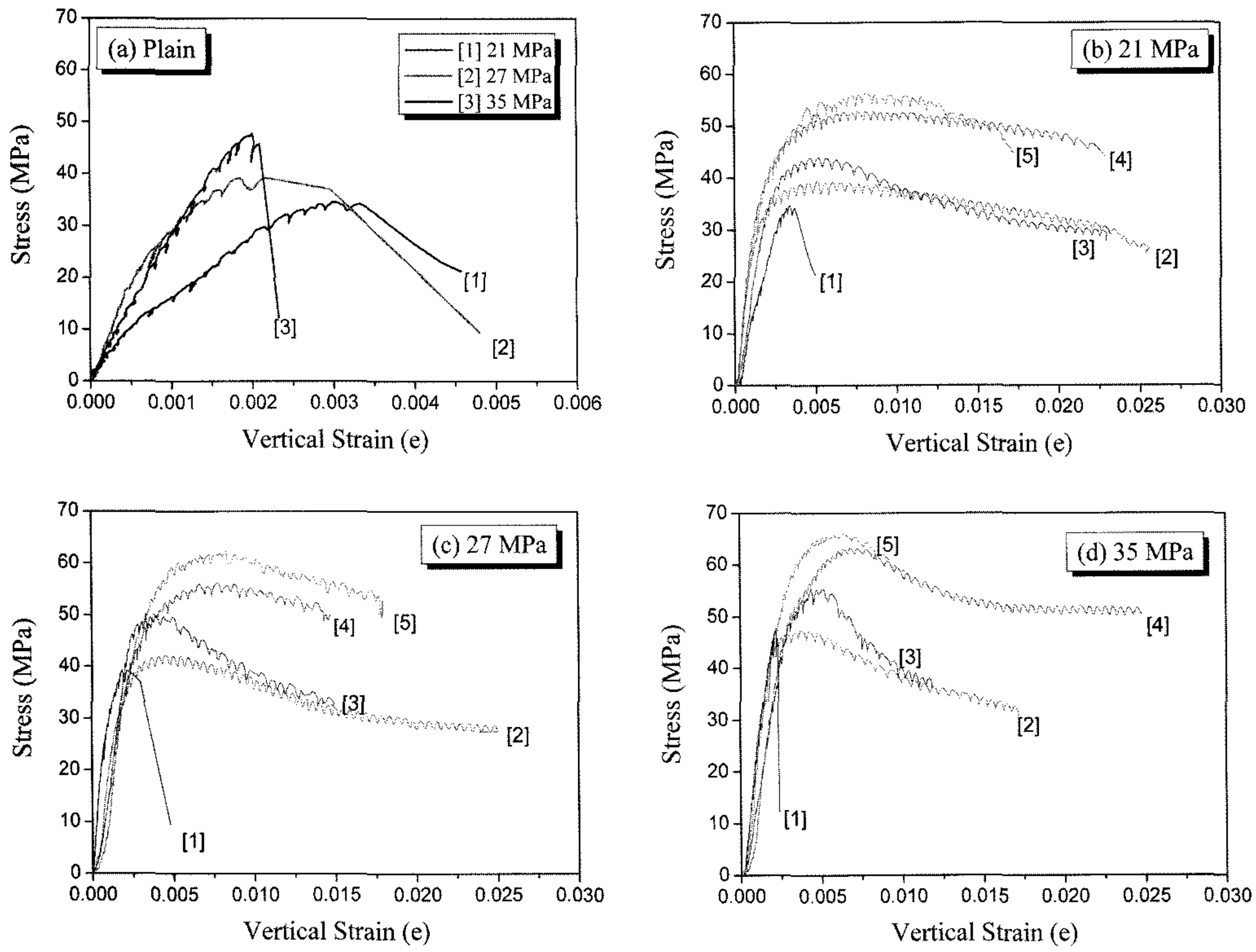
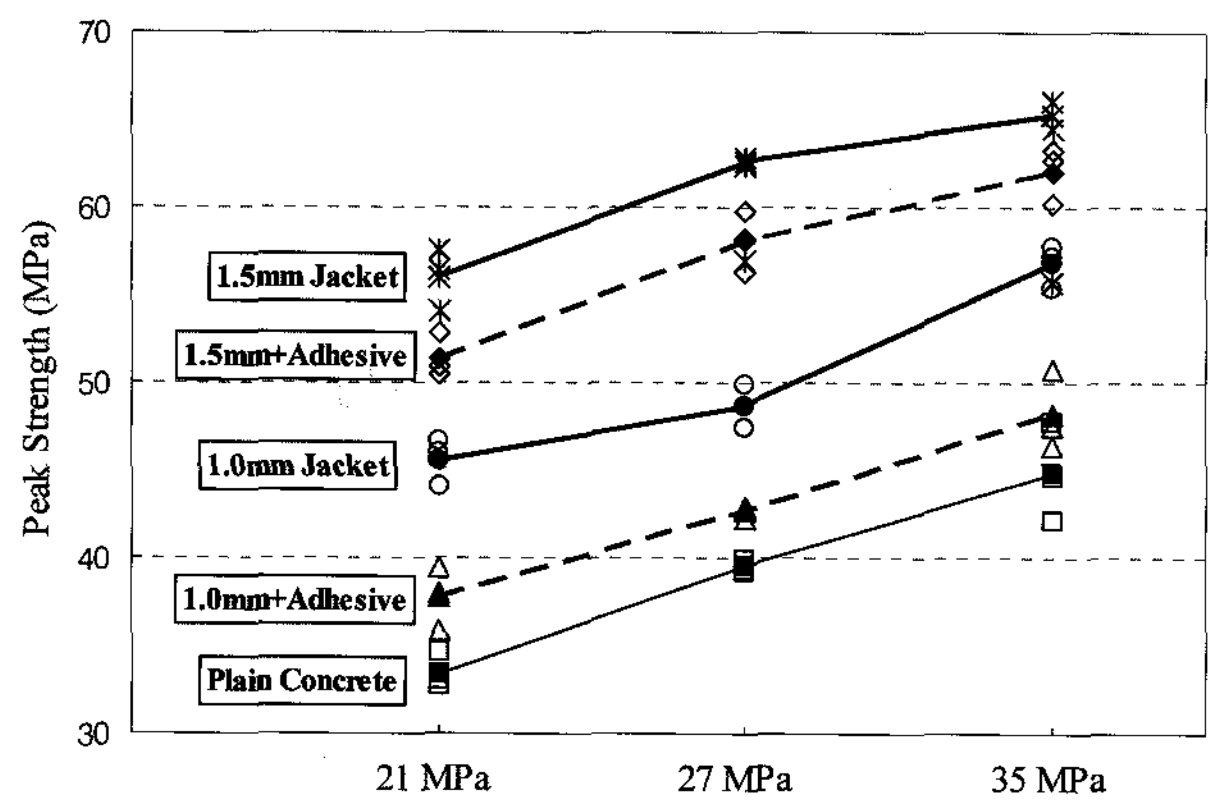
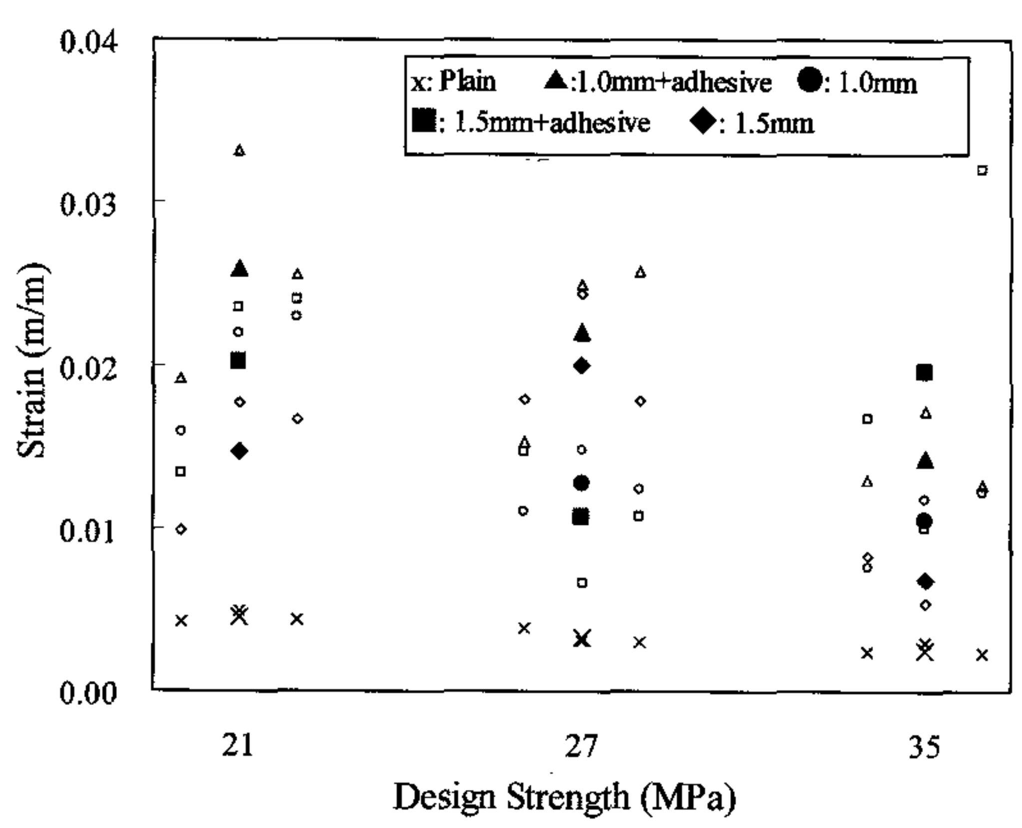


Fig. 5 Test results of plain and confined cylinders by two split jackets; the legend of (b)-(d) is [1]: plain, [2]: 1.0 mm + adhesive, [3]: 1.0 mm, [4]: 1.5 mm + adhesive, and [5]: 1.5 mm



(a) Peak strengths



(b) Failure strains

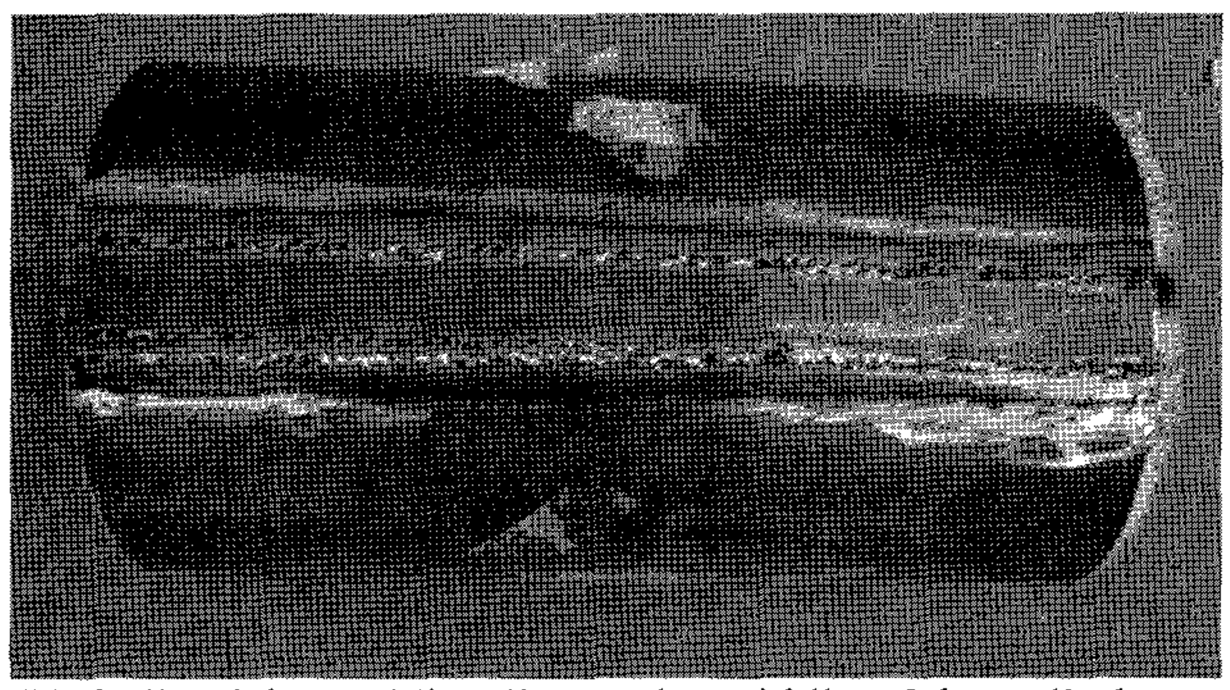
Fig. 6 Comparison of Peak strengths and failure strains of plain and jacketed cylinders

ets. For the case of 1.5 mm jackets, the peak strengths with the adhesive are 51.4, 58.1, and 62.0 MPa, respectively. Also, the values for 1.5 mm jackets alone are 56.0, 62.6, and 65.3 MPa, respectively; each one from 1.5 mm jackets for 27 and 35 MPa concrete shows much lower strength than the other two and, thus, the values are excluded to calculate the above average. For 1.5 mm jackets, the adhesive produces lower strengths by 7 to 14%. Consequently, the adhesive is not helpful to increase fully the peak strengths of jacketed cylinders. The reason is assumed to be that the adhesive of 0.05 mm thickness acts as like a gap between a steel jacket and concrete surface. The Young's Modulus of the adhesive is approximately 2.0 GPa that is about 1/100 and 1/12 of steel and concrete Young's modulus, respectively (Kim, 1995). Therefore, when a concrete cylinder is bulged laterally, the jacket with the adhesive is not activated immediately.

The second point is that, as expected, 1.5 mm jackets produce higher strength than 1.0 mm jackets. The peak strengths with 1.0 mm jackets are 45.6, 48.7, and 56.8 MPa, respectively, and the corresponding values with 1.5 mm jackets are 56.0, 62.6, and 65.3 MPa. Thus, 1.5 mm jackets increase the strengths more by 19 to 35%. The last point is that the jacketing effect is better on the lower strength concrete. 1.0 mm jackets increase the strengths by 36.3, 23.3, and 26.7% for 21, 27, and 35 MPa concrete cylinders, respectively. Also, 1.5 mm jackets increase the strengths by 67.6, 58.4, and 45.6%, respectively.

In Fig. 6(b), the failure strains of the jacketed cylinders are arranged; the failure strain means the axial strain of a cylinder when the jacket is fractured or experienced the full plastic deformation. Enhancement in ductility is addressed as increment in the failure strain of confined con-


(a) Full plastic deformation of steel


(b) Split of the welding line at the middle of the cylinder

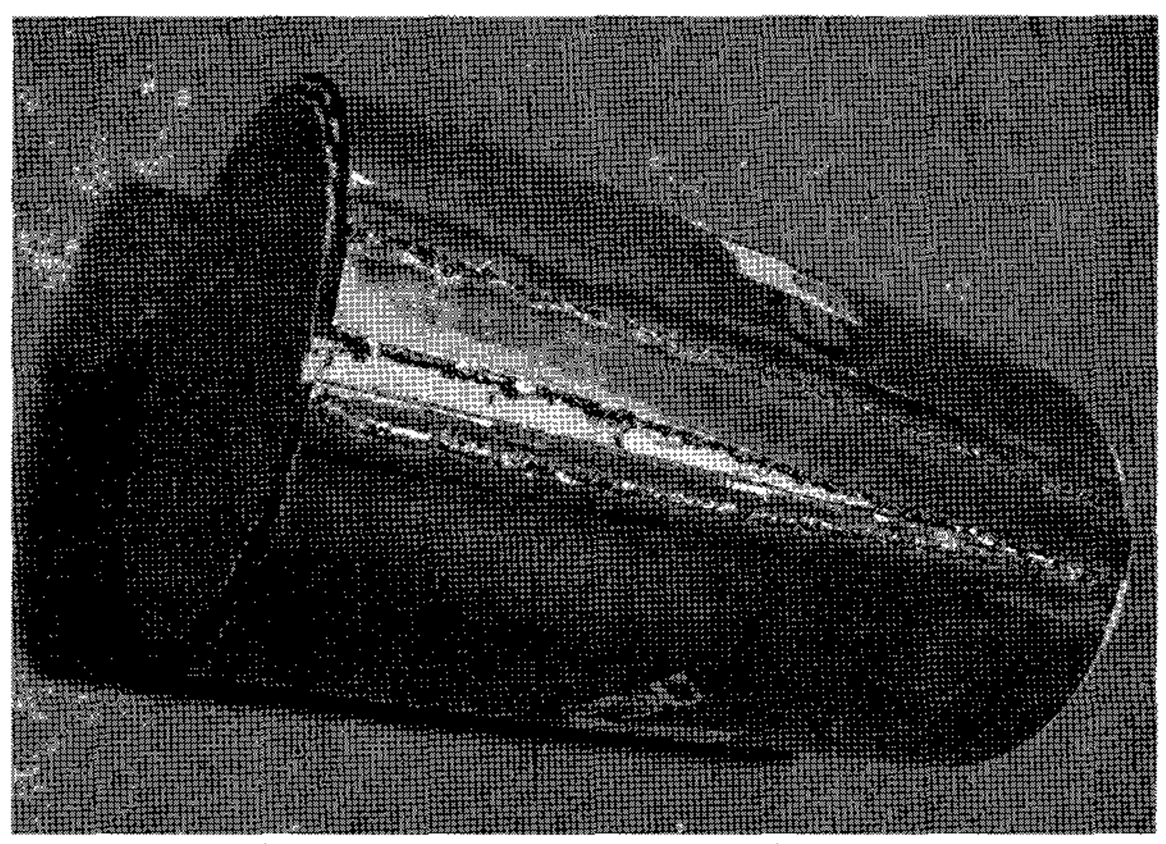

(c) Split of the welding line at the end of the cylinder

Fig. 7 Failure modes of jacketed cylinders crete comparing to that of plain concrete. The failure strains of jacketed cylinders are varied from 2.6 to 5.8 times of those of the plain cylinders. However, the failure strains are less than 0.04 and scattered irregularly; which is much less than the failure strains from a previous study (Li et al., 2005a). As shown in Figs. 7(b) and (c), the failure occurred at the welding line between strips and jackets. This jacketing method does not induce the full plastic deformation of steel jackets and, thus, the failure strains become small relatively. However, in Fig. 7(a), the jacket is experienced the full plastic deformation at the middle of the cylinder and the welding line is not fractured yet. In the case, the failure strain is larger than that of the cases of Figs. 7(b) and (c). Thus, the failure strain depends on the welding condition in this jacketing method.

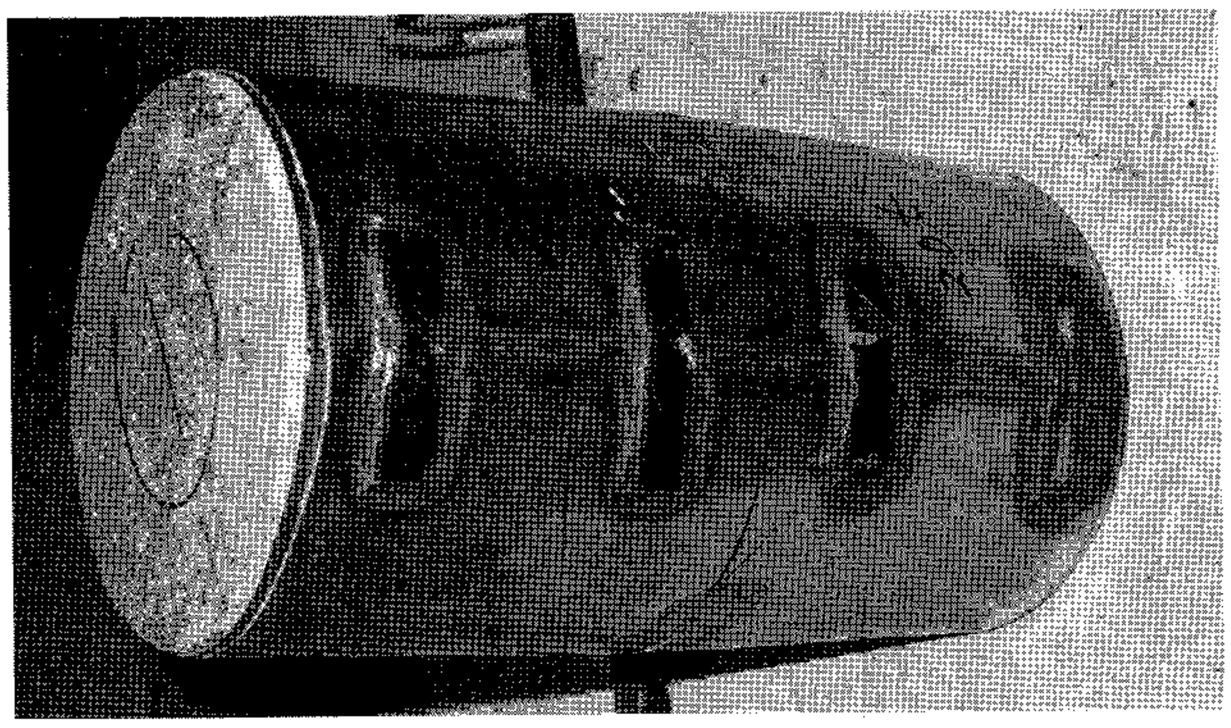
4. 12 Concrete Cylinders And Whole Steel Jackets : Part II

The second compressive test of 12 concrete cylinders is conducted to improve the performance of the proposed jacketing method. Instead of two split jackets, a whole jacket of stainless steel and lateral strip bands shown in Fig. 8(a) are used to confine a cylinder. In this case, the dimension of a jacket is 290 mm 481 mm (HW). The width of the jacket is larger than the perimeter of the cylinder by 10 mm to lap one side over the other side. The procedure to fabricate a jacketed cylinder with a whole jacket is similar to the previous one; 1) wrap a jacket around a cylinder, 2) press the jacket by clamps, 3) weld the overlap line, and 4) weld strip bands crossing the welding line. The strip bands are used to prevent the failure at the welding line because it is proved to be a weak point in the previous tests.

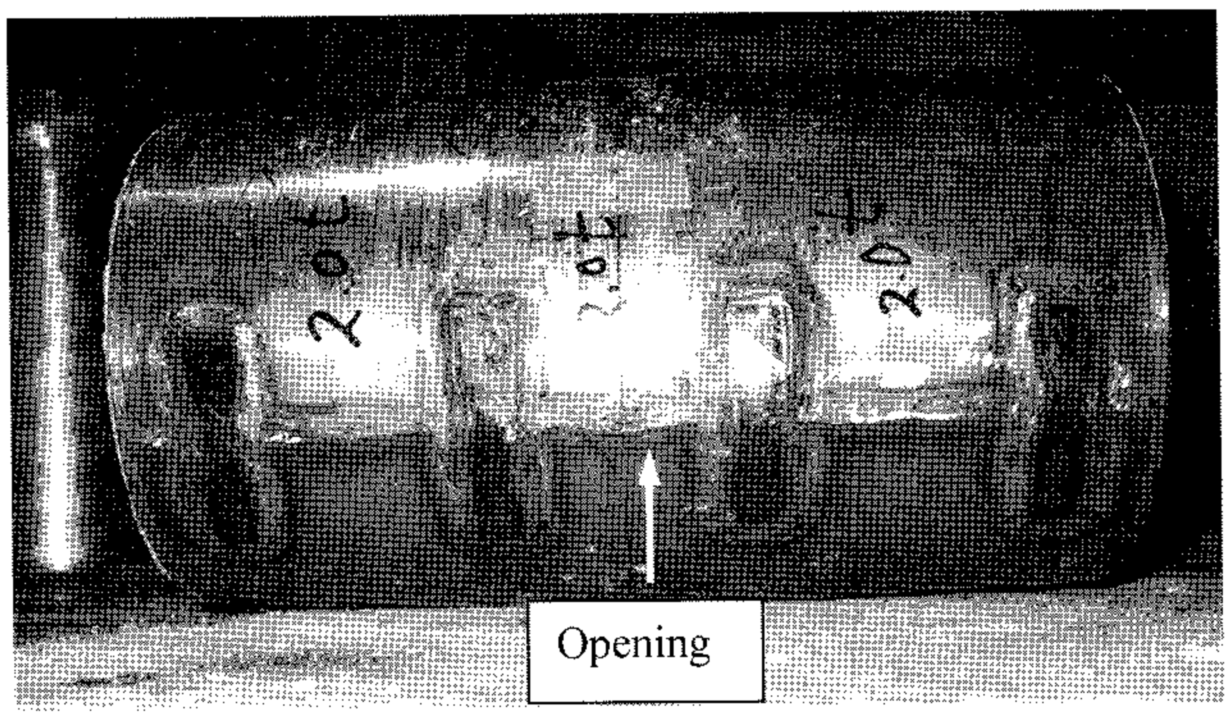
In the tests, the thicknesses of the jackets are 1.0, 1.5, and 2.0 mm. Meanwhile, the 2.0 mm jacket consists of two 1.0 mm jackets; which is called a double-layer jacket. The yield strength of the steel jackets is estimated as 400 MPa experimentally. A double-layer jacket is completed following the above procedure. At first, the inside jacket is installed and, then, the outside jacket is installed over the previous one. Then, band strips are welded to reinforce the welding line. The goal of the second tests is to check whether 1) a whole jacket does work to induce the full plastic deformation of steel and 2) a double-layer jacket works as a single jacket of the same thickness. In the second tests, the adhesive was not used because it was proved as not effective.

The stress-strain curves of 3 plain and 9 jacketed cylinders are shown in Fig. 9(a). The average peak strength of 3 plain cylinders is 26.8 MPa. The average peak streng- ths with 1.0, 1.5, and 2.0 mm jackets are 39.6, 44.7, and 49.8 MPa, respectively, and the increments of the strength are 47.8, 66.8, and 85.8%. The quantities of increments are similar to those of the first tests. Fig. 9(b) shows the peak strengths of the jacketed cylinders versus the thickness of the jackets. The solid triangles in the figure represent the mean strengths of the three types of jacketed cylinders. The linear regression of the three mean streng- ths shows almost a perfect linear relationship between the peak strength and the thickness of the jackets; the value of R^2 is very close to 1.0. This result proves that the double-layer jacket consisting of two 1.0 mm jackets works as a single jacket of 2.0 mm thickness.

The compressive loading was stopped at the strain of 0.04 except one not because of the fracture of the jackets but because of limitation of the displacement transducer to measure the axial deformation. However, a cylinder confined by 1.5 mm jacket was tested to reach over the strain of 0.06, which is 12 times larger than the failure strain of the plain concrete, and was not fractured at the welding line. Fig. 8(b) shows a bulged cylinder and the welding line that is not fractured yet. Therefore, a whole jacket

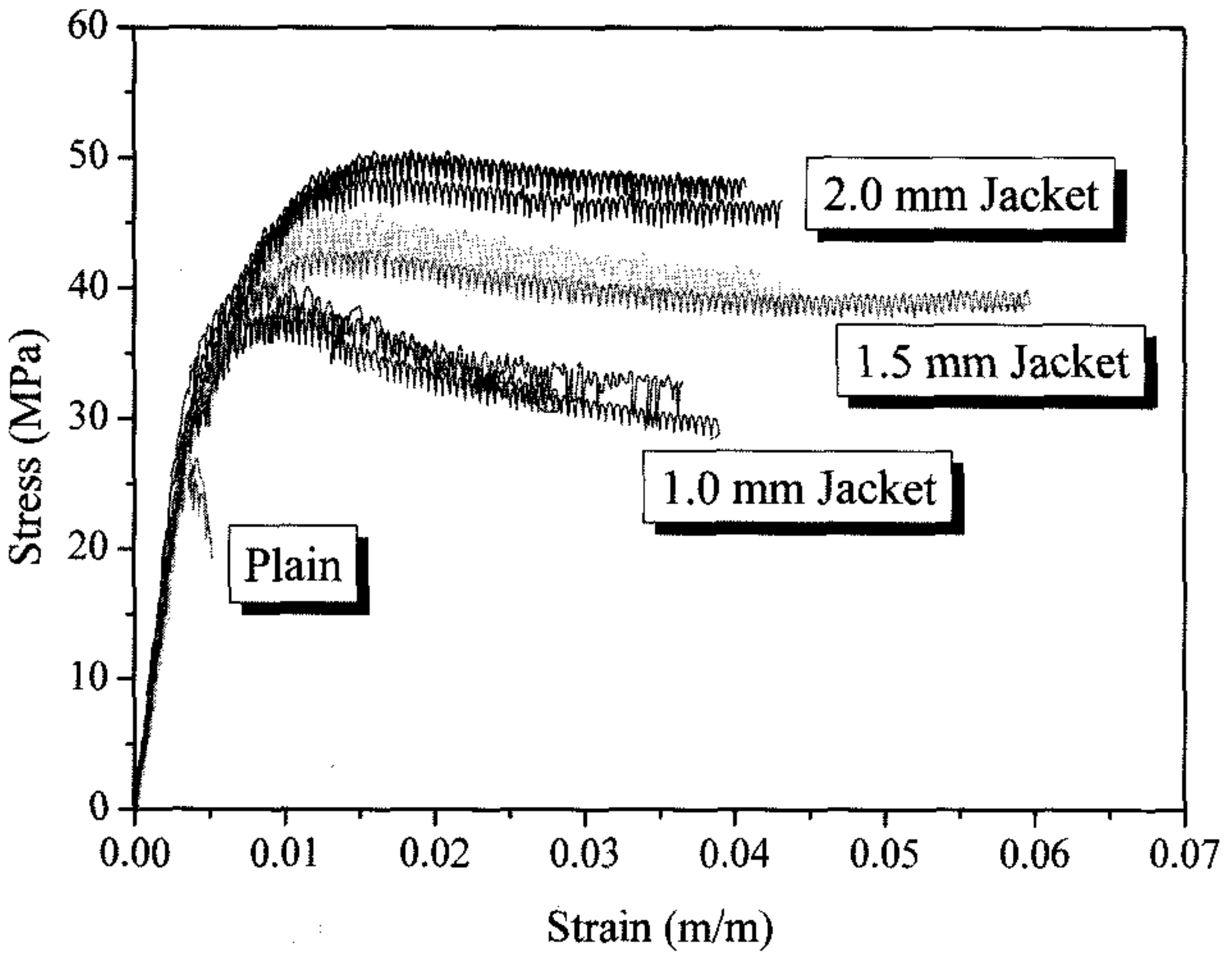


(a) Shape of a cylinder before a compressive test

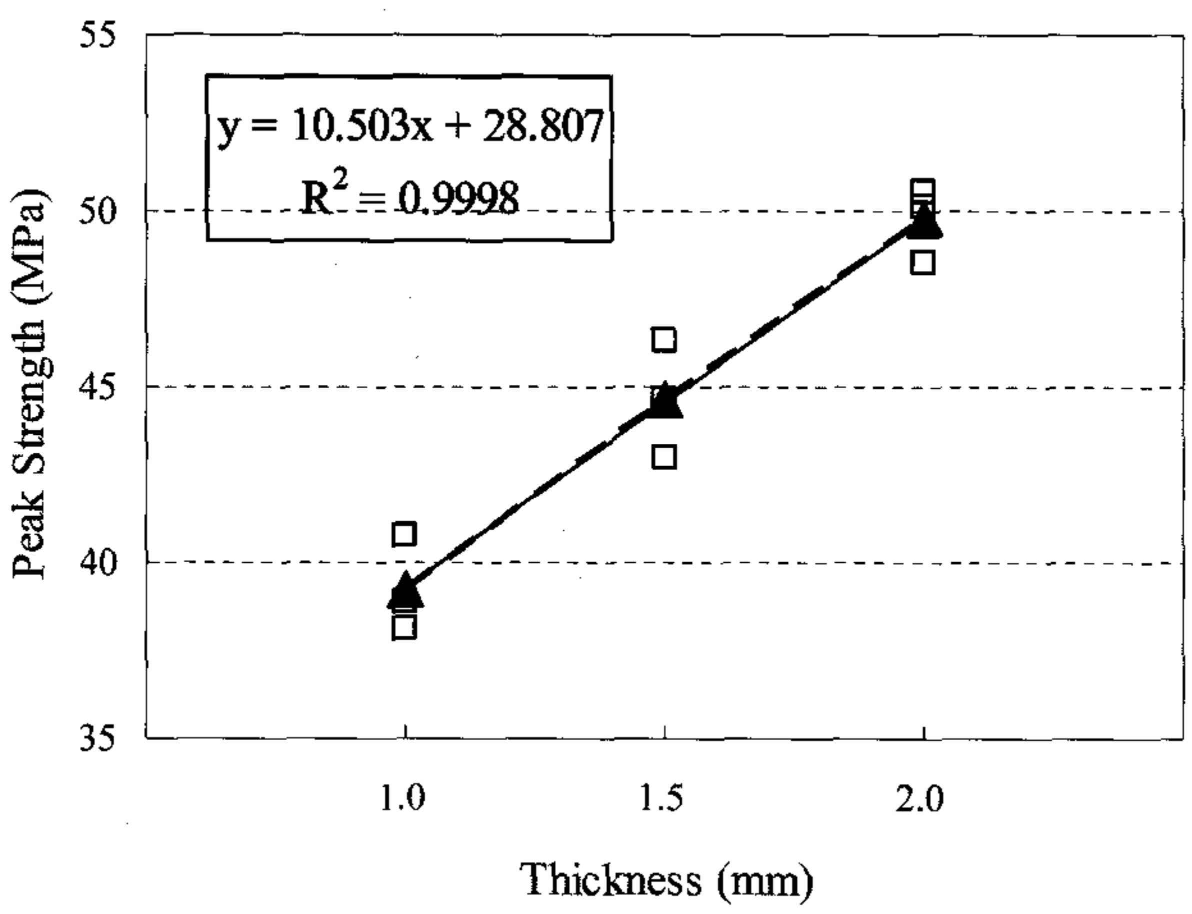


(b) Shape of a test-completed cylinder

Fig. 8 Shape of a confined cylinder by a whole jacket and strip bands



(a) Stress-strain curves



(b) Peak strength

Fig. 9 Compressive test results of the confined cylinders by a whole steel jacket

with lateral strip bands works to produce full plastic deformation of steel jackets.

5. Comparing The Results with Constitutive Model of Concrete Confined by Steel Jacket

Several constitutive models of confined concrete by conventional hoop reinforcement have been proposed (Saatcioglu and Razvi, 1992; Hoshikuma et al., 1997). Among them, Mander's model is frequently cited (Mander et al., 1988). However, the Mander's model can not be applied for the concrete confined by steel jackets because it was proposed for conventional lateral reinforcement. Li et al. (2005a, 2005b) proposed a constitutive model of concrete

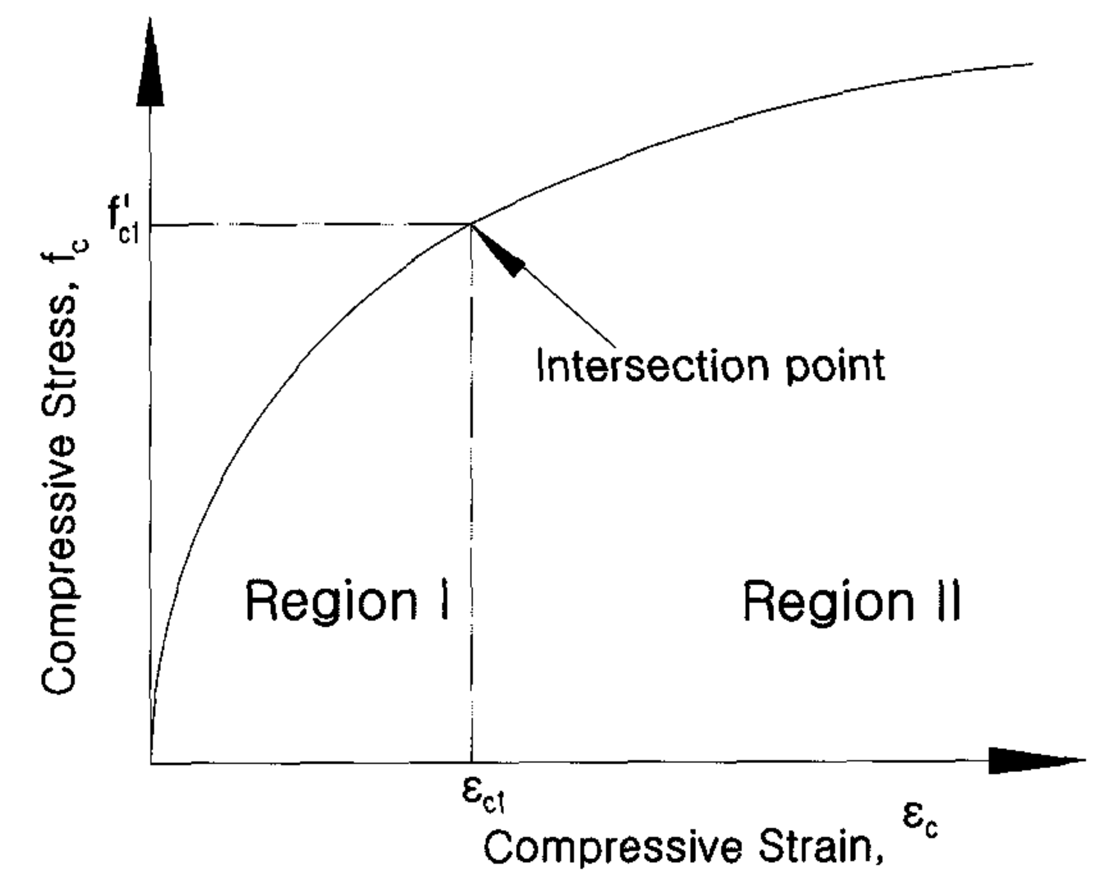


Fig. 10 Constitutive model of confined concrete by a steel jacket

confined by steel jackets and lateral reinforcement. The stress-strain relationship of the model has the two regions of 'Region I' and 'Region II' as shown in Fig. 10. The strength at the intersection point, f_{c1}', is the function of the strength of plain concrete, f_{c0}', and lateral confining strength, f_l, as follows.

$$f_{c1}' = f_{c0}' + 1.519 f_l^{1.18} \text{ [MPa]} \quad (1)$$

where $f_l = f_{l1} + f_{l2}$

f_{l1} and f_{l2} are the effective confining strengths provided by lateral reinforcement and steel jackets, respectively.

$$f_{l1} = \frac{1}{2} k_e \rho_s f_{yh} \quad (2a)$$

$$f_{l1} = \frac{1-(s/2d_s)}{1-\rho_c} \quad (2b)$$

where k_e = the confinement effective coefficient, ρ_s = the transverse reinforcement ratio, and f_{yh} = the yield strength of transverse reinforcement. Also, s = the clear spacing between the spiral, d_s = the diameter of the spiral, and ρ_c = the ratio of the area of the axial steel to the area of the core of the section.

$$f_{l2} = \frac{2 \times t \times E_{cs} \times \varepsilon_{cs}}{D} \quad (3)$$

where t = the thickness of the steel jacket, E_{cs} = the elastic modulus of the steel jacket, D = the diameter of the cylinder, and ε_{cs} = the yield strain of the steel jacket. This term is zero in this study since there is not any reinforcement in concrete cylinders.

The strain of ε_{c1} is corresponding to the strength of f'_{c1} and expressed as below;

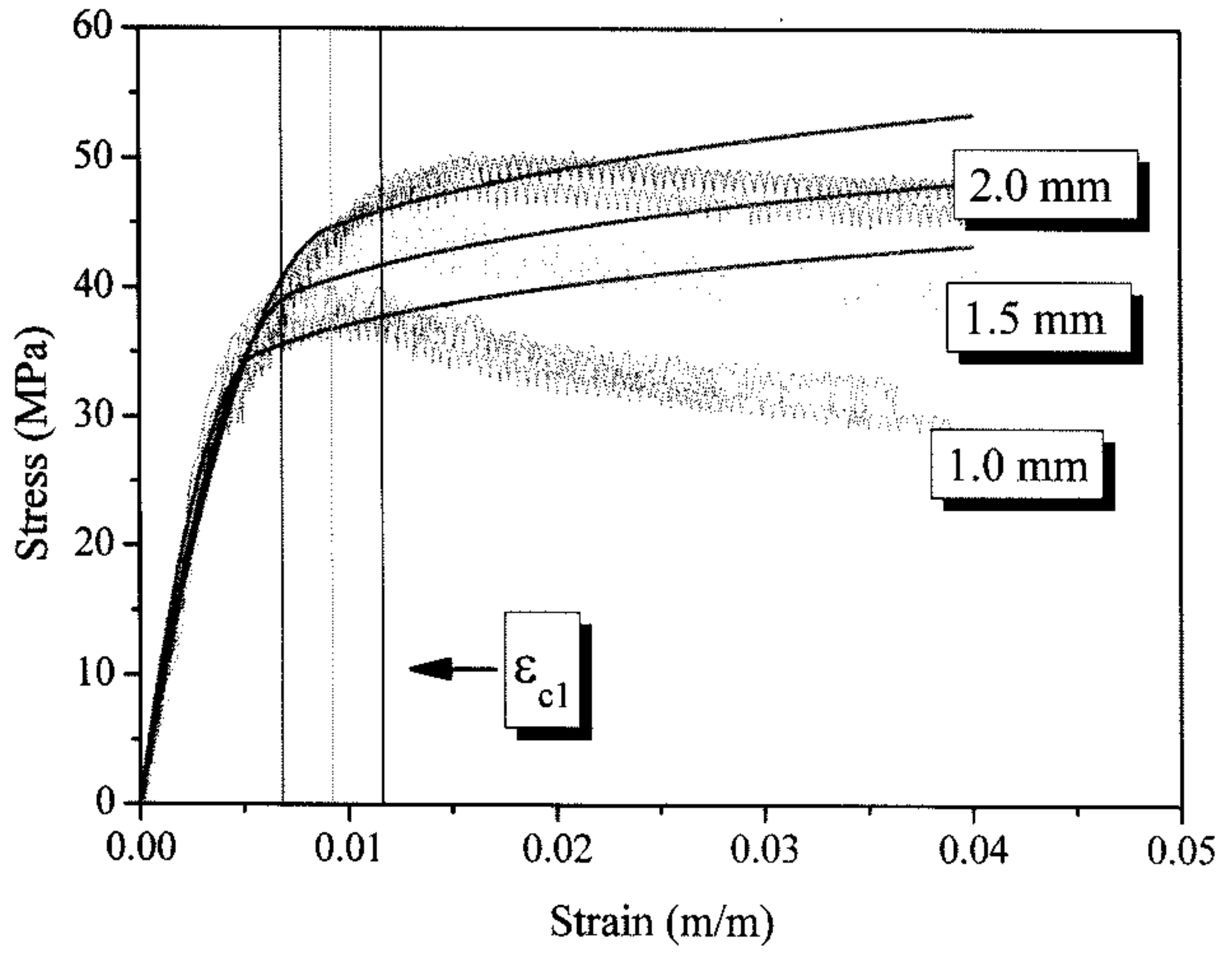


Fig. 11 Comparison of the test results to the constitutive models

$$\varepsilon_{c1} = \varepsilon_{c0}\left[1 + 12.2\frac{f_l}{f_{c0}'}\right] \tag{4}$$

where ε_{c0} = the strain of plain concrete for the ultimate strength that is estimated as 0.002.

The stress-strain relationship is represented by two curves for each region; the formulations are given by

1) For the strain $0 \le \varepsilon_c \le \varepsilon_{c1}$ (Region I)

$$f_c = f_{c1}'\left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right)\left[(n-1)\left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right) + (n-2)\right] \tag{5}$$

2) For the strain $\varepsilon_c \ge \varepsilon_{c1}$ (Region II)

$$f_c = f_{c1}'\left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right)^n \tag{6}$$

where $n = 0.1 + 0.075\left(\frac{f_1}{f_{c0}'}\right)$; that is the power of the power law in Region II.

The Li's models are compared to the experimental results of the second test in which a whole jacket is used to confine a cylinder. Fig. 11 shows 9 experimental results of 1.0, 1.5, and 2.0 mm jackets and their corresponding Li's models. Also, in the figure, the vertical lines represent the strains at the intersection points for the three models; the strains are 0.00682, 0.00923, and 0.01164 for 1.0, 1.5, and 2.0 mm jacket, respectively. The comparison indicates that the experimental results are consistent with the Li's models almost perfectly in Region I. Table 1 compares the values of f_{c1}' at the intersection points from the experimental curves and the models. The errors from the comparison are 2.52, 7.66, and 10.36% for 1.0, 1.5, and 2.0 mm jacket, respectively; the errors increase with increasing the thickness of the jackets. Table 2 shows the estimated secant stiffnesses of the models and experimental results and the maximal error is about 10%.

Just after Region I, stiffness hardening is observed from the experimental curves; that is corresponding to the constitutive models. However, after that, stiffness softening is developed from all jackets; that is not observed in the models. The whole jackets do not maintain the stiffness hardening because of the opening of the welding line. Fig. 8(b) shows the opening at the welding line of a test-completed cylinder. The steel jacket's stress becomes larger than the welding strength and, then, the welding line starts to open. However, the opening does not mean the fracture of the welding line since the ductile behavior of the jackets is observed. The opening is developed locally at the mid-point of a cylinder where the hoop strain is maximized. The initial strain of the softening can be denoted as the cross point between the models and the experimental curves. Based on this definition, the initial strains of the

Table 1. Comparing the strength of f_{c1}' between the models and the experimental results

Thickness (mm)	ε_{c1} (%)	Model, f_{c1}' (MPa)	Experimental, f_{c1}' (MPa)				Error (%)
			Sp1	Sp2	Sp3	Average	
1.0	0.682	37.96	34.86	39.25	36.97	37.03	2.52
1.5	0.923	44.67	42.88	42.34	39.25	41.49	7.66
2.0	1.164	51.81	46.51	46.51	47.82	46.95	10.36

Table 2. Comparing the secant stiffness between the models and the experimental results

Thickness (mm)	Model (MPa)	Experimental (MPa)				Error (%)
		Sp1	Sp2	Sp3	Average	
1.0	9332	9350	8600	8300	8750	6.65
1.5	8417	8837	6967	7100	7634	10.25
2.0	7866	9709	7671	7670	8350	5.80

softening are approximately estimated as 0.0131, 0.0167, and 0.0198 for 1.0, 1.5, and 2.0 mm jackets, respectively. Theses strains are 1.7 to 1.9 times larger than the intersection strains. Therefore, the hardening continues to about two times from the intersection strain, ε_{c1}, where the steel jacket is yielded. The comparison between the experimental results and the Li's models indicates that the proposed steel jacketing method in this study shows an equal performance to that of the conventional steel jacketing method to increase the strength and the ductility of the jacketed cylinders.

6. Conclusions and Observations

This paper proposed a new steel jacketing method for reinforced concrete columns. The method uses lateral pressure on steel jackets to guarantee a tight contact between steel jackets and concrete surfaces and, thus, does not need the grouting between steel jackets and concrete surface. The two series of compressive tests of concrete cylinders are conducted to improve the performance of the proposed method. In the first test, two split steel jackets are used to wrap a cylinder. The results of the first test indicate that 1) the effect of the jacket is better for lower strength concrete, 2) the adhesive used to attach the steel jacket on concrete surface is proved as not effective, 3) the ductility of the jacketed cylinder depends on the welding condition between the split jackets, and 4) the thicker jacket increases the ultimate strength of a jacketed cylinder more. In the first test, the two-split-jacket system does not produce full plastic deformation of a steel jacket. Therefore, in the second test, a whole jacket is used to confine a cylinder with lateral strip bands to reinforce the welding line of the jacket. Also, a double-layer jacket consisted of two steel plates is introduced. The whole jacket system extracted the full plastic deformation of the jackets. The welding line was not fractured due to the reinforcement of the strip bands. The double-layer jacket is improved to show an equal performance to the single jacket of the same thickness. The relationship of the peak strength versus the thickness of jackets is almost linear.

Finally, the experimental results of the second test are compared with the constitutive model of the confined concrete of steel jackets. The comparison indicates that 1) the experimental results are almost perfectly consistent with the constitutive models up to the steel jacket's yield. However, after the yield, although the model shows a continuous hardening, the experimental curves reveal softening. The reason of the softening is the opening of the welding line. If the stress of the steel jackets is higher than the welding strength, the welding line starts to open. Thus, the hardening can not be continued and the stiffness degrading is appeared. The initiation of the opening of the welding line does not mean the fracture of the jackets and the whole jacket system shows satisfactory ductile behavior.

The proposed new steel jacketing method uses lateral pressure provided externally to attach steel jackets on concrete surface. It does not need the grouting between steel jackets and concrete surfaces. Thus, the method can install jackets on RC columns easily at any location, bottom, middle or top, and is estimated as effective as the conventional steel jacketing method to use the grouting.

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