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A REVIEW OF DIRECT FASTENING STEEL JACKET FOR STRENGTHENING OF REINFORCED CONCRETE COLUMNS

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ABSTRACT

A novel retrofit method for reinforced concrete (RC) columns using a direct fastening steel jacket has been newly developed. This novel retrofit method features a simple and quick retrofit procedure, whereby high-strength fasteners are actuated and driven through to connect steel angles, steel plates and the concrete surface surrounding the column. Steel plates in direct fastening steel jackets can carry axial load and lateral load directly because they are appropriately interacted with RC columns. Direct fastening connections in direct fastening steel jackets behave in the manner of transverse reinforcement, which can share shear load and generate passive confinement to concrete columns. Given that limited research has been undertaken on direct fastening steel jackets, this paper summarizes state-of-the-art work on the experimental study, theoretical study and design methods of direct fastening connections used to strengthen RC columns. Interesting findings include the significant improvement of the strength and flexural stiffness of RC columns strengthened by the developed method and subjected to axial and cyclic lateral loads, as observed in experiments. Furthermore, the theoretical study based on fundamental mechanical derivations lays down the groundwork for the development of the design methods of RC columns strengthened by this innovative method.

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1. Introduction

RC columns are used to resist vertical loads and lateral loads in frame structures. However, when they experience a fire or earthquake event, load carrying capacity and flexural stiffness can be impaired. Such damaged RC columns may fail to resist subsequent extreme loading events, such as impact or earthquake. This situation becomes more critical during seismic events, where seismic demand exceeds the designed capacity [1-8]. It can be seen from Fig. 1 that damaged structures with reduced flexural stiffness may suffer more notable lateral deformation during a strong earthquake, as shown in Fig. 1. When seismic displacement demand exceeds inelastic displacement capacity, the collapse failure of columns may occur. Restoring flexural stiffness is an effective method by which to decrease displacement demand. Indeed, although previous retrofitting methods have mainly concentrated on improving the strength of RC columns, the necessity to enhance the flexural stiffness of RC columns is also necessary.

The use of a fiber-reinforced polymer (FRP) jacket is an effective strengthening method that can improve the strength of an RC column by way of the passive confinement effect. However, it does not effectively enhance the flexural stiffness of RC columns [9-12]. Moreover, FRP jacketing is made up of composite materials with poor fire resistance, which impedes their prevalent application. To overcome these disadvantages, a strengthening method increasing the cross-sectional area was studied [13-17]. Although structural behavior can thereby be improved, this method cannot meet the demand for rapid strengthening because the adding of the further layer of concrete is time consuming. Although steel jackets can overcome these disadvantages, few studies have been conducted.

A steel jacket formed by four steel angle brackets at the corners of the RC columns was first proposed by Nagaprasad et al. [18]. Two adjacent steel angle brackets were connected by steel battens using a welding connection. Experimental results indicated that this method can improve the flexural strength and flexural stiffness of RC columns. However, flexural stiffness increase was limited (44%) as it was only provided by four steel angle brackets.

Roca et al. [19] subsequently conducted experimental tests on RC columns retrofitted with steel jackets. In their tests, a load mechanism of monotonic lateral loading with constant axial loading was used. Similar conclusions were drawn. Sahoo and Rai [20] applied this strengthening method to an RC frame, and dynamic tests were carried out on a strengthened and unstrengthened RC frame. Based on the natural frequencies of strengthened and unstrengthened RC frames, it can be concluded that the flexural stiffness of the strengthened RC frame was improved by 20%. More recently, Xu et al. [21] proposed a steel cage that was not affixed to the footing but rather was composited with the RC column using steel glue. Flexural stiffness was found to increase by 60%, which is also insignificant. The mechnisms of these two strengthening methods were very similar, wherein the function of four steel angle brackets was identical to the longitudinal rebar. The contribution to resisting bending behavior was provided by the limited cross-sectional area of the four steel angle brackets. Therefore, enhancement of the flexural stiffness of the strengthened RC columns was not significant.

It can be seen that few studies have focused on enhancing the flexural stiffness of RC columns. Furthermore, the improvement of existing steel jackets on flexural stiffness is not remarkable. Therefore, a strengthening method that can significantly enhance flexural stiffness is necessarily developed. Here, a novel retrofit method for RC columns using a direct fastening steel jacket has been newly developed. In this method, an innovative direct fastening connection – distinguishable from the traditional welding connection – was utilized [22-26]. In this paper, a comprehensive review on the experimental study and theoretical study of this innovative strengthening method is conducted to facilitate its application to practical design.

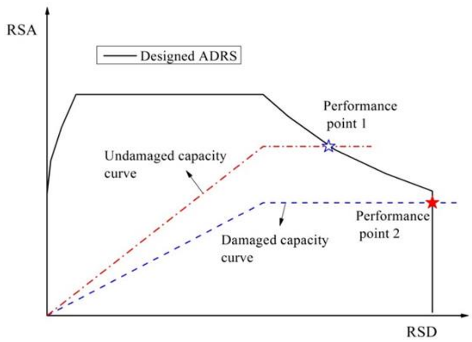

Fig. 1 Capacity spectrum subject to fire attack or earthquake event

2. Direct fastening steel jacket

A novel steel jacket is developed herein, as illustrated in Fig. 2. This novel retrofit method features a simple and quick retrofit procedure, as a result of the direct fastening connection method used. In this method, high strength fasteners can be easily driven into two steel plates using an actuated gun. Compared to welding connections, this method is more easily manipulated. With this proposed steel jacket, steel plates contribute to axial and lateral load capacity because they are composited with the RC column. Direct fastening steel connections can provide passive confinement and contribute to shear strength because their behavior is analogous to the transverse reinforcement. Therefore, the strength, stiffness and deformability of RC columns can be improved.

This direct fastening jacket and fastening connection can directly undertake shear force, and can resist the in-plane shear force generated from passive confinement. Therefore, the behavior of direct fastening connections subjected to in-plane shear force should be comprehensively studied. The mechanism of RC columns composited with the developed direct fastening steel jacket and subjected to axial and lateral loading can then be studied. Based on these studies, a design procedure can be developed. Therefore, the behavior of direct fastening connections subjected to in-plane shear force is first reviewed. The behavior of RC columns composited with the developed direct fastening steel jacket and subjected to axial and seismic loading is then analyzed before the design procedure is reviewed.

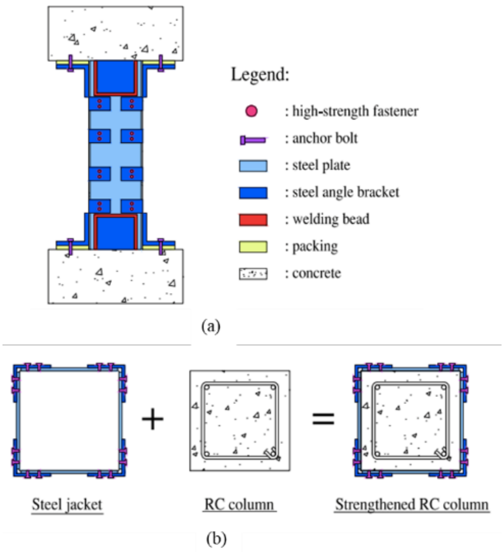

Fig. 2 Proposed strengthening scheme: (a) front view; and (b) plane view

3. Behavior of direct fastening connections subjected to in-plane shear force

One hundred samples connected by two types of fastener were tested, under in-plane shear force [22]. Parameters, including number of fasteners, spacing of fasteners, arrangement of fasteners, surface condition of fasteners and effect of protuberance were examined; see Fig. 3.

Typical displacement versus in-plane shear force is shown in Fig. 4. It can be seen that this type of connection possesses preferable plastic deformation before failure. This lays a foundation for the prevalent application of this connection. To better describe this process, a simplified three-linear curve (i.e., OABC) is proposed, by which the passive confinement force provided by this direct fastening connection in the strengthened RC columns can be determined. To determine this simplified three-linear curve (see Fig. 4), the effective stiffness, bearing shear strength and displacement at pull-out point should be separately studied.

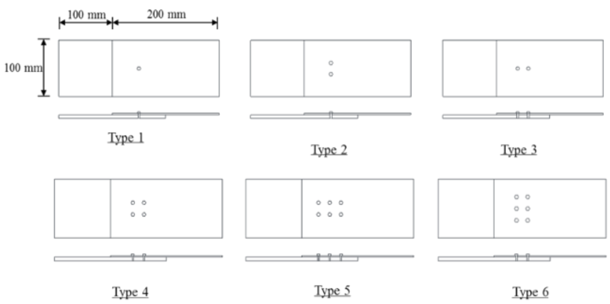

Fig. 3 Types of connection

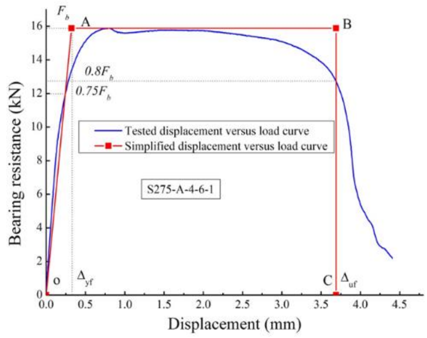

Fig. 4 Displacement versus load curve

3.1. Effective stiffness

Effective stiffness can be used to obtain the deformation of a direct fastening connection when the deformation lies within the OA stage. A direct fastening connection is formed using high strength fasteners driven into two steel plates. Therefore, fastener diameter, thickness of steel plate and the elastic of the steel plate are the critical parameters affecting the effective stiffness [22]. This is given as:

$$K_{ef}=\varphi_{kn}\varphi_{kef}E_p t_p d_n \tag{1}$$

where φ_{kn} is the factor considering the effect of fastener number (FN), which is calibrated by test results and given in **Table 1.** φ_{kef} represents the factor considering the effect of other parameters excluding the above-mentioned three critical parameters. It is also calibrated by test results and a value of 0.017 is recommended. E_p, d_n and t_p are the elastic modulus of the steel plate, nominal fastener diameter and thickness of the steel plate, respectively. In general, the fastener diameters are 3 mm and 4 mm, such that effective stiffness is mainly affected by fastener number and thickness of the steel plate, considering that the elastic modulus of steel is almost constant.

Table 1
Recommended values of FN factor

Number of fasteners	n=1	n=2	n=3	n=4
FN factor	1	1.4	1.9	2.1

3.2. Bearing shear strength

In accordance with the expressions used to determine the bearing capacity of bolt connections recommended in previous specifications (e.g., ANSI/AISC 360-16), the expression determining the bearing capacity of direct fastening connections is given as [22]:

$$F_b=\varphi_{fp}\varphi_{fk}\alpha_{br}d_n t_p f_{up} \tag{2}$$

where f_{up} is the tensile strength of the steel plate. In this innovative direct fastening connection, when fasteners are driven into steel plates, protuberance is generated which positively contributes to bearing capacity. Therefore, a factor (φ_{fp}) was introduced to consider this effect. Furthermore, the surface condition of the fasteners (i.e., knurling) also plays a key role in bearing capacity. A factor (φ_{fk}) for the effect of knurling is thus brought in. Other stochastic effects are included in bearing capacity factor (α_{br}). The recommended values of these three factors are presented in **Table 2**.

3.3. Ultimate displacement

Owing to the fact that plastic deformation is significantly larger than elastic deformation (which can be seen from the displacement versus in-plane shear force curve), the rotation of the fastener determines the ultimate displacement of direct fastening connections, as shown in the following expression:

$$\Delta_{uf}=\frac{t_1+t_2}{2}\theta_f \tag{3}$$

where θ_f is the ultimate rotation of the fastener, which corresponds to pull-out time. When the friction force between the fasteners and holes of the steel plate can no longer resist the pull-out force, pull-out failure occurs, indicating that the ultimate rotation is affected by the surface condition of the fasteners. Therefore, the ultimate rotation of different types of fastener should be separately determined. According to the test results, ultimate rotations of 0.43 rad and 0.75 rad are recommended for the two types of fasteners, respectively.

Table 2
Recommended values of three factors in bearing capacity

α_{br}		Ψ_{fp}		Ψ_{fk}	
Tight contact with top steel plate	Non-tight contact with top steel plate	With pre-drilled holes on connected plates	Without pre-drilled holes on connected plates	Unknurled fasteners	Knurled fasteners
1.6	1.36	1.0	1.35	1.0	1.17

4. Behavior of RC columns strengthened by direct fastening steel jackets subjected to axial loading

4.1. Experimental study

To investigate the behavior of RC columns encompassing direct fastening steel jackets, eight specimens were designed and tested [23]; see Fig. 5. To better distinguish between the specimens, they are each named using a notation. For example, S-3-76.5-1 represents a thickness of the steel plate used of 3 mm, connected by a direct fastening connection consisting of one fastener, with a connection spacing of 76.5 mm. Four parameters, including connection spacing, number of fasteners, thickness of steel plate and end connection, were examined.

Both axial load capacity and ductility are greatly enhanced by the proposed direct fastening jacket. For the two specimens in which the steel jacket is joined with one fastener and two fasteners, peak axial loading is 1548 kN and 1765 kN, respectively. This demonstrates that the confinement effect for connections with a higher number of fasteners is more notable. Regarding the effect of connection spacing, the peak axial loads of S-3-42.5-1, S-3-76.5-1 and S 3 116.5 1 are 1498 kN, 1548 kN and 1676 kN, respectively. Smaller connection spacing results in a smaller slenderness ratio for steel plates, which delays buckling time. Therefore, when the axial strength is determined, the effect of confinement and buckling should be considered.

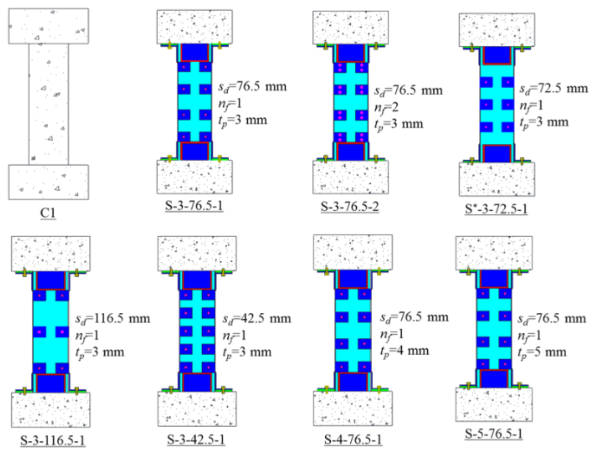

Fig. 5 Types of connection sample

4.2. Theoretical study

4.2.1. Confined concrete strength

As shown in Fig. 6, the concrete was divided into three parts to distinguish between the confinements of the concrete core. Concrete core 1 is confined by both stirrups and direct fastening connections. Concrete core 2 is only confined by direct fastening connections while concrete core 3 comprises plain concrete without confinement.

When a column is subjected to axial loading, transverse deformation generates due to Poisson's effect. If there is no transverse confinement, transverse deformation can expand freely; see the dashed line in Fig. 7(a). In the case of transverse confinement, interaction between the concrete and transverse reinforcement occurs. As a result, passive confinement stress (see Fig. 7(b)) acts on the concrete core and transverse deformation is constrained; see the solid line in Fig. 7(a). Transverse reinforcements can be regarded as beams on an elastic foundation, and then the governing equations are derived [24].

$$\frac{d^4\omega_x}{dy^4}+\frac{\kappa_x s_a}{E_{TR}I_{TR}}(\omega_x-\delta_x)=0 \tag{4a}$$

$$\frac{d^4\omega_y}{dx^4}+\frac{\kappa_y s_a}{E_{TR}I_{TR}}(\omega_y-\delta_y)=0 \tag{4b}$$

$$\kappa_x=\frac{1}{\frac{d_c}{2}}\frac{E_c(1-\mu_c)}{(1+\mu_c)(1-2\mu_c)}(1+\frac{\mu_c}{1-\mu_c}\frac{b_c}{d_c}) \tag{4c}$$

$$\kappa_y=\frac{1}{\frac{b_c}{2}}\frac{E_c(1-\mu_c)}{(1+\mu_c)(1-2\mu_c)}(1+\frac{\mu_c}{(1-\mu_c)}\frac{d_c}{b_c}) \tag{4d}$$

where κ_x and κ_y in Eqs. (4c) and (4d) are the bending stiffness of transverse reinforcement provided by the RC column along the x and y axes. With the exception of the elastic modulus (E_c) and Poisson's ratio (μ_c) of the concrete, the geometric parameters of the depth (d_c) and width (b_c) of the RC column also affect the bending stiffness. $E_{TR}I_{TR}$ represents the mechanical characteristic of the deflection of the transverse reinforcement. I_{TR} and E_{TR} are the second moment and elastic modulus of transverse reinforcement, respectively. Deflections of the transverse reinforcement along the x and y axes are respectively depicted by ω_x and ω_y while transverse expansion of the RC column along the x and y axes is respectively denoted by δ_x and δ_y. s_a is the width of the transverse reinforcement.

The passive confinement stress generated from direct fastening connections and stirrups, combining corresponding boundary conditions, can then be determined according to the derived governing equation. Once passive confinement stress is derived, confined concrete strength can be obtained.

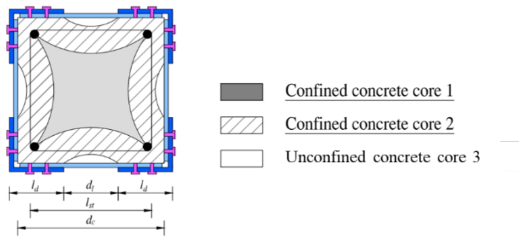

Fig. 6 Division of concrete cross-section

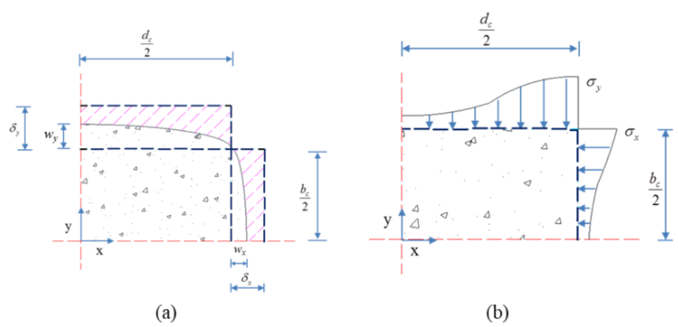

Fig. 7 Confinement effect: (a) profile of plane deformation; and (b) profile of passive confinement stress

4.2.2. Buckling strength of longitudinal steel rebar

Longitudinal rebars are restrained by concrete cover. Longitudinal rebar buckling may occur following concrete cover spalling. During the post-buckling process, part of the cross-section of the longitudinal rebar is unloaded. Because loading stiffness and unloading stiffness are different, the average stress of the cross-section of the longitudinal rebar should be used instead of the local stress on the stress-strain curve of the steel material. Dhakal and Maekawa [27] verified that the former average stress is less than the latter local stress; see Fig. 8. They proposed a mothod to estimate this average stress and the expressons are given by:

$$\sigma_{\text{buck}}=\begin{cases}1-(1-\dfrac{\sigma^*}{\sigma_l^*})(\dfrac{\varepsilon_{ave}-\varepsilon_{yl}}{\varepsilon^*-\varepsilon_{yl}}), & \varepsilon_{yl}<\varepsilon_{ave}\le\varepsilon^*\\ \sigma^*-0.02E_s(\varepsilon_{ave}-\varepsilon^*), & \varepsilon_{ave}>\varepsilon^*\end{cases} \tag{5}$$

where ε_{ave} is the average strain. It is equal to the value when the maximum axial load of the strengthened RC column is reached. σ^* and ε^* are used to depict the strain and stress of the turning point in Fig. 8. σ_l^* is the corresponding stress on the simplified stress-strain curve of the steel material at a strain of ε^*. ε_{yl} is the nominal yield strain of longitudinal rebar.

4.2.3. Buckling strength of steel plates

In this proposed steel jacket study, the steel plates are only restrained at the direct fastening connections. Steel plates between connections are simply supported by the RC column. When steel plates are subjected to compressive stress, outgoing buckling occurs. This was investigated in a previous test. To predict the buckling strength of steel plates, a theoretical study was conducted by Shan et al. [24] and an expression was proposed combining the experimental results.

$$P_{p,critical}=\frac{4\pi^2 Dd_p}{s_d^2}(1-\alpha_i) \tag{6a}$$

$$D=\frac{E_p t_p^3}{12(1-\mu_p^2)} \tag{6b}$$

where D is the bending stiffness of steel plates that are restrained by direct fastening connections at two ends. E_p, μ_p and t_p are the elastic modulus, Poisson's ratio and thickness of the steel plate, respectively. α_i ($0<\alpha_i\le 1.0$) is the initial imperfection factor, which is used to consider imperfections induced during the manufacture and welding processes. It is an empirical factor and was calibrated in accordance with experimental results.

$$\alpha_i=1.046-\frac{0.73\lambda_{sr}}{100} \tag{7}$$

It can be seen that this factor is related to the slenderness ratio (λ_{sr}) of the steel plates, which is defined by s_d/t_p.

Based on the above-mentioned methods, the strength of confined concrete core 1, confined concrete core 2, unconfined concrete core 3, longitudinal steel rebar and steel plates can be predicted. As a result, the axial loading capacity of the strengthened RC columns can then be determined.

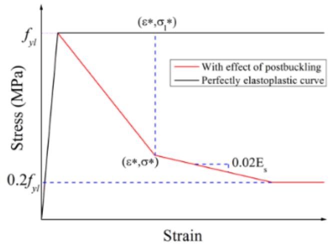

Fig. 8 Stress-strain curve of longitudinal rebar

5. Behavior of strengthened columns subjected to seismic loading

5.1. Experimental study

To further investigate the mechanical behavior of RC columns encompassing the direct fastening steel jackets under investigation, subject to seismic lateral loading, eight specimens were designed and tested. Four parameters, including connection spacing, number of fasteners, thickness of the steel plate and axial load ratio (ALR), were examined [25]. The configuration of each specimen is shown in Fig. 9. The notation criterion follows that used for the specimens under axial load action, except that the ALR is added in. For example, the label of S-0.16-4-60-4 represents the ALR of the specimen being 0.16.

Lateral load capacity, ultimate drift ratio and flexural stiffness were examined. A larger ALR negatively affected the seismic behavior of the strengthened RC column, as expected. Reduced connection spacing means a smaller slenderness ratio, which improves the buckling behavior of steel plate. In response, the seismic behavior of a strengthened RC column using the steel jacket with closer connection spacing is preferable, which accords with observations from experimental study. The behavior of direct fastening connections was also investigated. It was found that two fasteners were sufficient to maintain the stability of the direct fastening connection. Regarding steel plate thickness, the seismic behavior of strengthened RC columns using a steel jacket with thick steel plates was greatly improved.

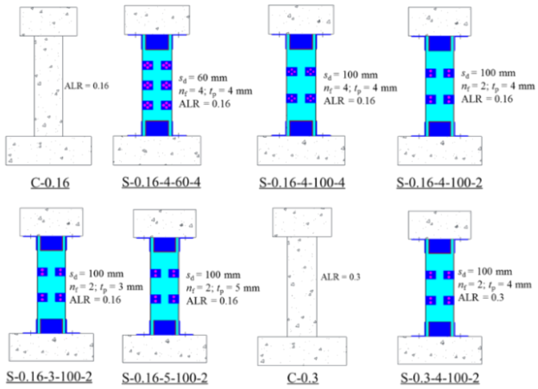

Fig. 9 Specimen configurations

5.2. Theoretical study

5.2.1. Lateral load capacity

Following the plane-section assumption, the stress distribution profile can be obtained (see Fig. 10), based on which the expressions that can be used to predict lateral load are derived [30]. Because the ends of the steel jackets were fixed, detaching between the RC column and the tensile steel plate perpendicular to the lateral load was observed in tests. The contribution of this steel plate to the lateral load should be reduced, considering this incompatible deformation. Therefore, a reduction factor of η_i=0.6 is introduced [25].

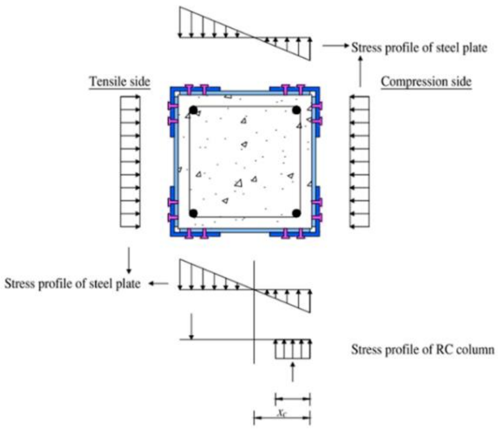

Fig. 10 Stress profile of strengthened RC column

5.2.2. Effective flexural stiffness

RC columns strengthened by this proposed method behave in the manner of composite columns. Therefore, the flexural stiffness of strengthened RC columns can refer to the expressions of flexural stiffness for composite columns in previous specifications [28,29].

$$K_i=(EI)_s+\alpha_c(EI)_c \tag{8}$$

It can be seen that flexural stiffness is generated from two areas: the RC column ($(EI)_c$) and the steel jacketing ($(EI)_s$). α_c is the reduction factor, which is taken as 0.6, in accordance with [28], while it is related to the ratio of the cross-sectional area of the steel jacketing ($A_{jacketing}$) to the cross-sectional area of the RC column (A_c), as recommended in [29].

$$\alpha_c = 0.45 + \frac{3A_{jacketing}}{A_c} \leq 0.9 \tag{9}$$

By comparing with the flexural stiffness obtained from the test results, it is recommended that reduction factor α_c takes a value of 0.6.

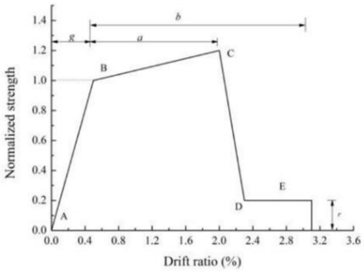

Fig. 11 Generalized force-deformation curve (ASCE 41-13)

5.2.3. Generalized force-deformation relationship

In order to undertake nonlinear analysis, the generalized force-deformation relationship is proposed in ASCE 41-13 [30], as shown in Fig. 11. Point B can be determined by effective stiffness and load capacity. Points C, D and E are controlled by three critical parameters: ALR, transverse reinforcement ratio and shear capacity ratio, which is defined by the capacity of flexural loading over the capacity of shear loading. This is an index used to identify failure mode. Because direct fastening connections act as stirrups in strengthened RC columns, this effect should be appropriately considered in the shear capacity and transverse reinforcement ratio.

For strengthened RC columns, the shear capacity contribution arises from three areas, as shown in the following equation:

$$V_0 = V_c + V_s + V_d \tag{10}$$

where V_c, V_s and V_d are the shear loading undertaken by the concrete, stirrup and steel jacketing, respectively.

Two components of V_c and V_s can be determined by:

$$V_c = 0.17\left(1 + \frac{N_0}{14A_c}\right)\lambda\sqrt{f_c'}\,d_c d_w \tag{11}$$

$$V_s = \frac{A_{st} f_{yst} d_w}{s_{st}} \tag{12}$$

where N_0 depicts axial loading acting on the RC column. f_c' denotes concrete strength. d_w is the effective depth of the RC column. λ is a facor which can refer to ACI 318-14 [32]. A_{st}, f_{yst} and s_{st} are the cross-sectional area, yield strength and spacing of stirrups, respectively.

Analogous to stirrups, the shear contribution arising from the direct fastening connection is given as [25]:

$$V_d = 0.5\frac{d_c}{s_d + d_d} 2nF_b \tag{13}$$

where F_b is the bearing strength of the direct fastening connection, which can be determined by Eq. (2). d_d signifies steel angle bracket length.

In strengthened RC columns, because direct fastening connections contribute to shear capacity, this effect should be considered in determining the transverse reinforcement ratio, which influences the generalized force-deformation relationship. As a result, an equivalent transverse reinforcement ratio, including stirrup ratio (ρ_v) and the contribution from the direct fastening connection, was proposed by Shan et al. [25].

$$\rho_{veq} = \rho_v + \frac{2nF_b}{f_{yst} d_c (s_d + d_d)} \tag{14}$$

The generalized force-deformation curve can then be determined, combining the recommended parameter values in **Table 3**. Fig. 12 presents a comparison of generalized force-deformation curves determined by the equivalent transverse reinforcement ratio and the stirrup ratio. This indicates that use of the equivalent transverse reinforcement ratio is appropriate.

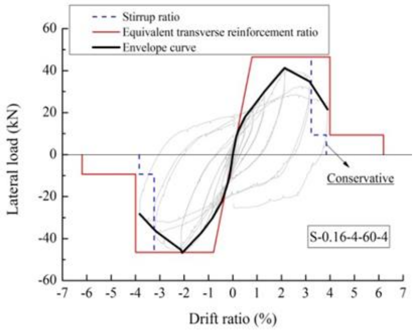

Fig. 12 Generalized force-deformation curve of strengthened RC column

Table 3
Parameters for generalizing force-deformation curve of RC column

	ALR	ρ_{veq}	Modeling parameter		
			a	*b*	*r*
Condition	≤ 0.1	≥ 0.006	0.035	0.060	0.2
(i)	≥ 0.6	≥ 0.006	0.010	0.010	0.0
	≤ 0.1	0.002	0.027	0.034	0.2
	≥ 0.6	0.002	0.005	0.005	0.0

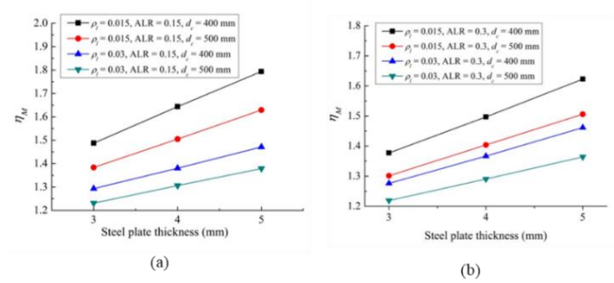

Fig. 13 Relationship between thickness of steel plates and enhancement ratio of flexural strength: (a) ALR = 0.15; and (b) ALR = 0.3

6. Design procedure of strengthened columns

To facilitate the application of the novel strengthening method in strengthening damaged RC columns with flexural strength and flexural stiffness deficiency, a design procedure was developed by Shan et al. [26]. In this section, the critical steps in the design procedure are presented.

Three parameters must be determined in direct fastening steel jackets: spacing of direct fastening connection, steel plate thickness and number of fasteners.

(1) Spacing of direct fastening connection

Preferable flexural failure is the expected failure mode in design. Existing lateral loading, flexural capacity and shear capacity should satisfy the following relationship to guarantee the occurrence of this failure mode:

$$V \leq V_{cap,stren} \leq 0.6V_{stren} \tag{15}$$

where V signifies the existing lateral load. V_{stren} and $V_{cap,stren}$ are the shear capacity and flexural capacity of the strengthened RC columns.

Since the existing lateral load is known, connection spacing can be determined by combining Eqs. (10) and (15). In this way, direct fastening connection spacing can be determined.

(2) Steel plate thickness

The flexural capacity of strengthened RC columns is related to the thickness of the steel plates. A parameter study was carried out to investigate the relationship between the thickness of steel plates and the enhancement ratio of flexural strength ($\eta_M = V_{cap,stren}/V_{cap}$, where V_{cap} is the flexural capacity of the RC column requiring strengthening). Fig. 13 shows the parameter study results, which can be used to select the thickness of steel plates during practical design.

(3) Number of fasteners

The axial load capacity and shear capacity of strengthened RC columns were influenced by the number of fasteners. It was evident from the experimental study on the seismic behavior of strengthened RC columns that two fasteners are sufficient to maintain connection stability. Therefore, the number of fasteners is initially taken as two.

The design procedure of strengthened RC columns is summarized in Fig. 14. Firstly, the flexural capacity of the damaged RC column (V_{cap}) should be estimated. Secondly, in accordance with the enhancement ratio of flexural strength ($\eta_M = V/V_{cap}$), the thickness of the steel plates can be determined from Fig. 13. Thirdly, connection spacing can be initially determined by satisfying the relationship set out in Eq. (15). Lastly, three conditions should be satisfied: Condition (i) should guarantee that flexural capacity is not less than lateral demand; Condition (ii) requires that the axial load ratio is not higher than 0.65, as recommended in EN 1998-1:2004 [31]; and Condition (iii) aims to keep the deformation demand of the strengthened RC column comparable to that of the undamaged RC column, which requires the effective flexural stiffness of the strengthened RC column to be comparable to that of the undamaged RC column. If these three conditions cannot be satisfied, the number of fasteners, direct fastening connection and steel plate thickness should be updated until these three conditions are satisfied.

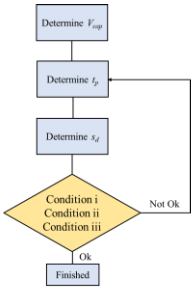

Fig. 14 Design procedure of strengthened RC column

7. Conclusions

This paper focuses on reviewing an innovative strengthening method (i.e., direct fastening steel jackets), by which the strength and flexural stiffness of RC columns can be simultaneously enhanced. Some key conclusions of this innovative strengthening method are summarized below.

(1) The protuberance and knurling of the surface impact positively on bearing capacity, the effects of which have been considered alongside two empirical factors. Effectiveness stiffness relates to the number of fasteners, fastener diameter, the elastic modulus of the steel material and steel plate thickness, while the expression of ultimate displacement is based on the rotation and friction mechanisms of the fastener.

(2) Both axial load capacity and deformation capacity are greatly improved. The confinement effect and buckling effect should be considered when axial load capacity is determined.

(3) The seismic behavior of strengthened RC columns is significantly improved. The detaching of tensile steel plate and buckling of compressive steel plate were observed during the test. To consider this effect, a reduction factor of 0.6 was introduced into the flexural capacity model. Effective flexural stiffness was significantly enhanced, which can be predicted by the expression recommended in EN 1994-1-1:2004. A method of evaluating the generalized force-deformation relationship was developed, in which an equivalent transverse reinforcement ratio was used.

(4) For the design procedure of strengthened RC columns, the number of fasteners, thickness of the steel plates and direct fastening connection spacing should initially be determined. For the initially determined direct fastening connection spacing and thickness of the steel plates, three specified conditions should be checked.

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