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Ultimate Deformation of Concrete Members and Suitable Material Property for Strengthening

コンクリート構造物の終局変形と耐震補強に必要な材料特性

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Abstract

In order to predict the ultimate deformation of reinforced concrete member, not only flexural strength and deformation but also shear strength and deformation after flexure yielding need to be estimated. This paper introduces the generic model to predict load – deformation relationship including post-peak range, which is applicable to concrete linear members reinforced with any material as tension and shear reinforcement, which can be either internal or external reinforcement, such as jacket. Considering the load – deformation relationship predicted by the generic model, this paper clarifies that suitable material property as shear reinforcement is large fracturing strain (>5%) together with moderate stiffness. This paper shows several good examples of the material with such a property, including polyethylene terephthalate (PET).

Key Words: ultimate deformation, generic model, large fracturing strain, PET
*キーワード：終局変形，一般化モデル，高伸長性，**PET***

1. Introduction

In order to have good seismic performance of structures, large enough ultimate deformation is vital. Brittle member failure caused by shear failure or tension fracture of reinforcement should be avoided to assure large ultimate deformation. The development of estimation model for ultimate deformation (ultimate deformation model) is necessary to predict the ultimate deformation. The ultimate deformation model can also provide us the information on material property for reinforcement, which can enhance ultimate deformation. This paper presents the generic model for prediction of ultimate deformation for concrete members with various tension materials as embedded reinforcement for new structures and externally bonded reinforcement for existing structures. Based on the presented model, the suitable material properties to achieve better ultimate deformation is illustrated.

2. Generic Ultimate Deformation Model

2-1 Definition of ultimate deformation

The ultimate deformation is usually defined as the point on the descending branch of the load (shear force) – deformation curve as shown in **Fig.1**. The curve I is the case of shear failure before flexural yielding. For the curve I, the ultimate deformation is the deformation at the peak load, which is the ultimate shear strength. The curves II, III and IV are the cases in which the ultimate deformation is reached after the flexural yielding when the remaining load carrying capacity becomes equal to the yielding load, V_y. The descending curve represent the reduction of load carrying capacity with increasing deformation. The curves II and III are the cases in which remaining shear strength decreases with increasing deformation, while the curve IV is the case in which remaining flexural strength decreases with increasing deformation. As shown in **Fig.1**, the remaining flexural strength reduction shows the most ductile manner. On the other hand, when the remaining shear strength is smaller than that of flexural strength, the ultimate deformation becomes smaller, meaning the less ductile behavior.

2-2 Remaining shear strength

Since the remaining shear strength determines the ultimate deformation, the estimation of the remaining shear strength is necessary. **Figure 1** shows the remaining shear strength with the black solid/broken lines, which decreases with the deformation increase. The shear strength, which we usually talk about, is the remaining shear strength when the deformation is zero.

The formulas to estimate the shear strength in design standards are usually experimental ones. JSCE Standard Specifications for Concrete Structures [1] provide the following equations for the shear strength, V_{total}, which is the summation of concrete contribution, V_c and shear reinforcement contribution, V_s:

$$V_{total} = V_c + V_s \quad (1)$$

$$V_c = 0.2\sqrt[3]{f'_{co}}\sqrt[4]{1000/d}\,\sqrt[4]{100\rho_s}(bd) \quad (2)$$

$$V_s = A_w f_{wy}(\sin\alpha + \cos\alpha)(z/s) \quad (3)$$

where f'_{co} is concrete compressive strength (MPa), d and b is effective depth and width of cross section, ρ_s is tension reinforcement ratio, is, A_w, f_{wy}, α and s is cross-sectional area, yield strength, angle to member axis and spacing of shear reinforcement, and z is truss arm length. Equation (2) indicates that not only concrete strength but also amount of tension reinforcement affect the shear strength. The study on shear strength of members with FRP as tension reinforcement indicates that the greater the stiffness of tension reinforcement is, the greater the shear strength is. The shear strength formula, therefore, should be dependent on the stiffness of tension reinforcement rather than the tension reinforcement ratio. In the case of steel shear reinforcement, the stress in shear reinforcement at shear strength can be approximated by its yield strength, since the stress in shear reinforcement is almost constant after its yielding. However, the stress in shear reinforcement cannot be estimated when the shear reinforcement is other than steel such as FRP which does not show yielding. If the shear strength is achieved when the shear reinforcement fractures, the stress in shear reinforcement at shear strength is the tensile strength of shear reinforcement. If the shear strength is achieved without the tension fracture of shear reinforcement, however, it is necessary to estimate the strain in shear reinforcement at shear strength. Considering those points, Sato et al proposed the shear strength model which can be applied to both members reinforced with steel internal reinforcement and with FRP internal reinforcement [2]. Sato et al's model shows that the shear strength depends on not only tension reinforcement stiffness but also shear reinforcement stiffness. Sato et al's model can also estimate the strain of shear reinforcement at shear strength.

The concept of Sato et al's model can be applied to estimate the remaining shear strength. As estimated by Sato et al's model, the remaining shear strength decreases after flexural yielding and after shear reinforcement yielding (see **Fig.1**). As deformation increases, strains of tension reinforcement and shear reinforcement increase. After the yielding of those reinforcement, the remaining stiffness continuously decrease with the increase in strains. Therefore, the remaining shear strength continuously decreases as the deformation increases. When the tension fracture of either tension or shear reinforcement happens, there is a sudden reduction in the reinforcement stiffness, resulting in the sudden reduction in the remaining shear strength. On the other hand, the tension fracture of tension reinforcement causes almost the total loss of flexural strength.

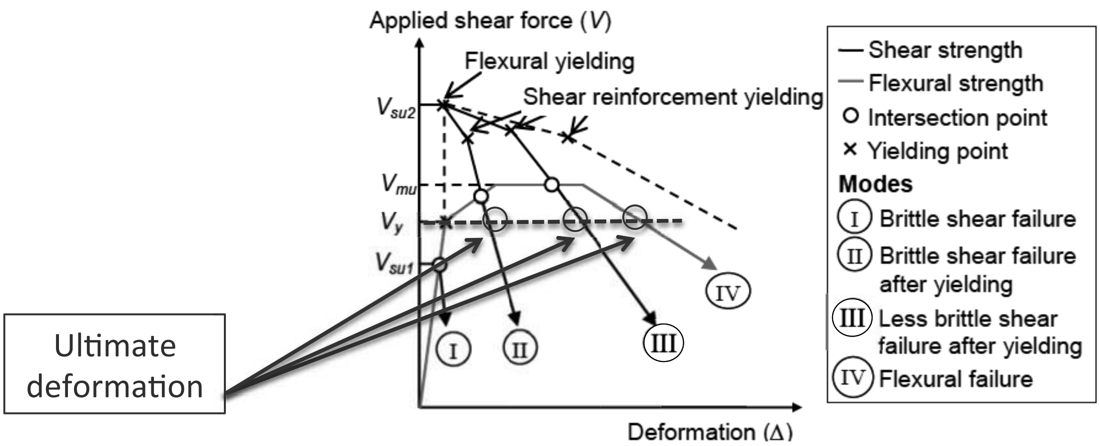


Fig.1 Ultimate deformation on load (shear force) – deformation curve

2-3 Generic model for ultimate deformation

In order to predict the ultimate deformation, the generic model for load – deformation relationship including post-peal range has been proposed [3]. This generic model consists of two strength models for flexure and shear and two deformation models for flexure and shear. The flexure model for both strength and deformation basically follows the section analysis as shown in **Fig.2**. The effects of confinement by not only tie reinforcement but also jacket on concrete strength in compression zone are considered by the following equations (see **Fig.3**):

$f_{lx,f} = (1/2)\rho_f \varepsilon_f E_f$, $f_{l,f} = (x_e\ /\ h)\rho_f \varepsilon_f E_f$ (jacket confinement) (4)

$f_{lx,w} = k_w \rho_w \varepsilon_w E_w$, $f_{ly,w} = k_w \rho_w \varepsilon_w E_w$ (tie reinforcement confinement) (5)

where

$$k_w = \frac{\left(1-\sum_{i=1}^{n}\frac{{w_i}^2}{6b_w h_w}\right)\left(1-0.5\frac{s'}{2b}\right)\left(1-\frac{s'}{2h}\right)}{1-\rho_{cc}}$$

ρ_f, ε_f and E_f is ratio, strain and elastic modulus of jacket. ρ_w, ε_w and E_w is ratio, strain and elastic modulus of tie reinforcement.

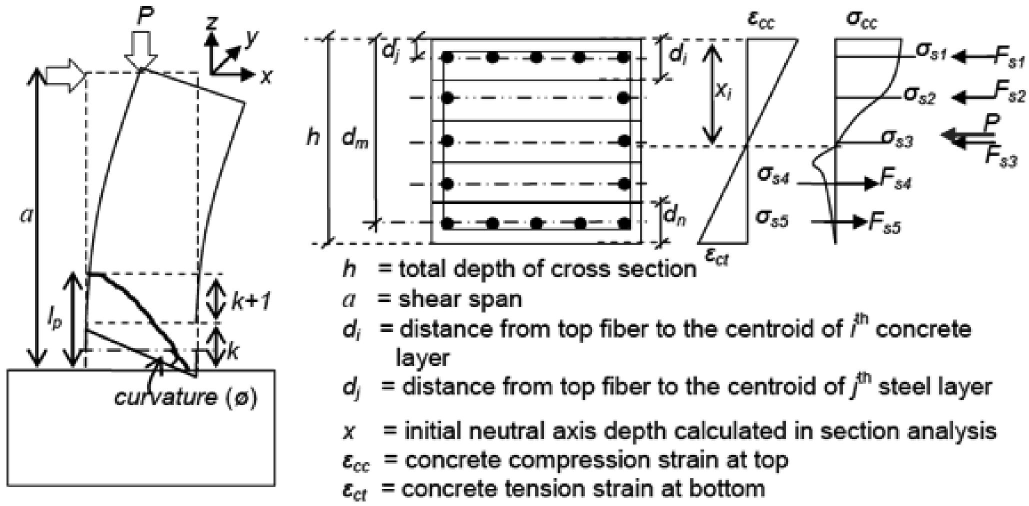


Fig.2 Section analysis for flexure model

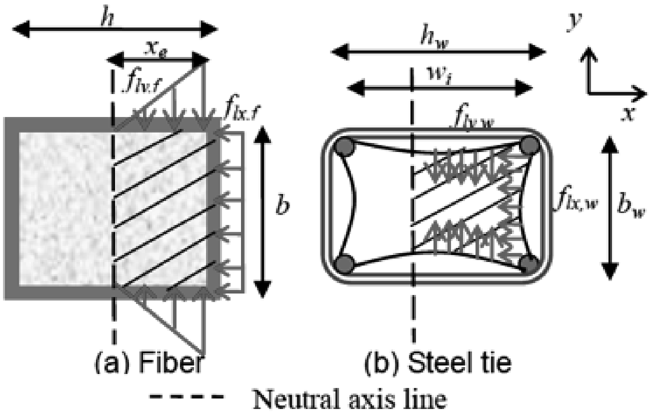


Fig.3 Confinement effects by jacket and tie reinforcement

The shear strength model is the modified Sato et al's model to predict more precisely the cases of concrete structures reinforced with steel internal reinforcement and FRP external reinforcement (jacket). According to the model, the shear strength, V_{su} is the summation of concrete resisting shear force, V_c and shear strength resisted by steel and FRP shear reinforcements, V_{s+f} as below (see **Fig.4**):

$$V_{su} = V_c + V_{s+f} \quad (6)$$

$$V_c = \beta_d \beta_p \beta_s \beta_w f_{vc} bd \quad (7)$$

$$V_{s+f} = bL_{web}(\rho_w \sigma_w + \rho_f \sigma_f) \quad (8)$$

where

$$f_{wc} = 0.2\sqrt[3]{f'_{ce}},\ \beta_d = \sqrt[4]{a/d},\ \beta_p = \sqrt{\frac{P}{2.5A_g f'_{co}}},\ \beta_s = \sqrt[4]{\rho_s E_{se}},\ \beta_w = \sqrt[4]{\rho_w E_{we} + \rho_f E_{fe}}$$

$$\sigma_w = \overline{\varepsilon_w} E_{we},\ \sigma_f = \overline{\varepsilon_w} E_{fe}$$

$$\overline{\varepsilon_w} = \frac{0.066}{\sqrt{a/d}+1}\left[e^{-0.12\sqrt{\rho_w E_{we}+\rho_f E_{fe}}+(4/\sqrt{\rho_s E_{se}})-0.2\sqrt{f'_{ce}}}\right]\left[1+\left(\frac{\sigma'_n}{f'_{ce}}\right)^{0.2}\right] \quad (9)$$

$$L_{web} = \frac{L_{str}}{\tan\theta},\ L_{str} = d - x_e$$

$$\frac{x_e}{x_i} = \left(\frac{1-e^{-0.42a/d}}{1+3.2^{-0.12(\rho_w E_{we}+\rho_f E_{fe})^{0.4}}}\right)\left[1+\left(\frac{\sigma'_n}{f'_{co}}\right)^{0.7}\right]\left[1.25e^{-0.08\left(\frac{\rho_s E_{se}}{1000}\right)}\right] \quad (10)$$

b is width of cross section, d is effective depth, a is shear span, L_{web} is projected shear crack length to member axis, ρ_s, ρ_w and ρ_f is ratio of steel tension reinforcement, steel and FRP shear reinforcement, E_{se}, E_{we} and E_{fe} is effective elastic modulus of tension reinforcement, steel and FRP shear reinforcement, f'_{co} and f'_{ce} is unconfined and confined concrete compressive strength, P is axial force, A_g is area of gross cross section, and σ'_n is axial compressive stress in concrete. Due to shear cracking the depth of compression zone (or neutral axis depth), x_e becomes smaller than the one. x_i obtained by the bending theory as indicated by Eq.(10). θ is strut angle (shear crack angle), which depends on various factors [4].

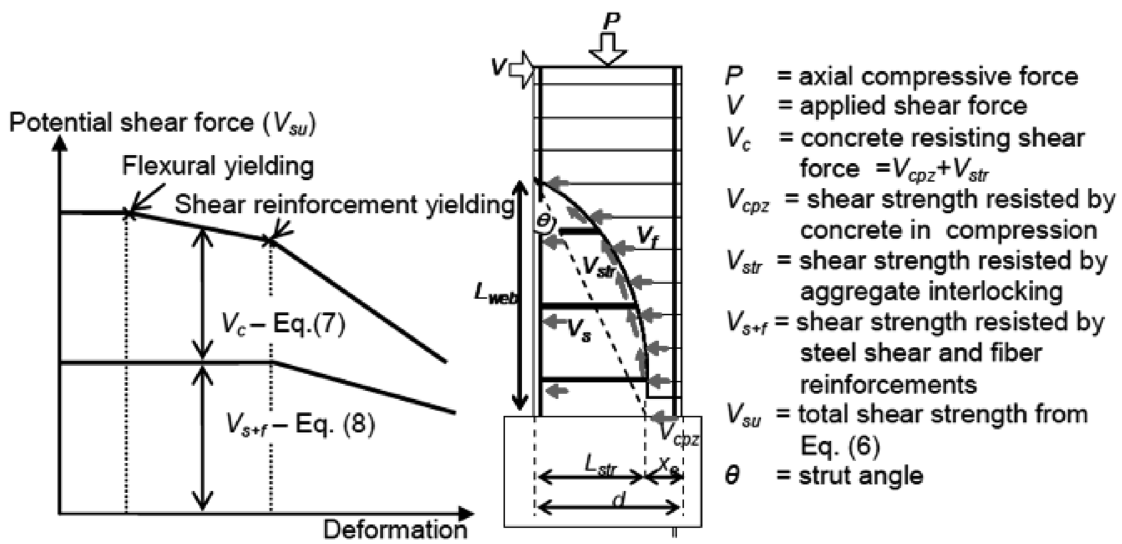


Fig.4 Shear strength model

The flexure deformation model considers the interaction effects with shear resisting mechanism. Once truss mechanism is formed after shear cracking, tension force in tension reinforcement is increased (see **Fig.5**). In tension reinforcement additional force is caused to balance the component in the longitudinal direction of diagonal compression force. Due to this force, the flexure deformation is increased. It is called as tension shift (or moment shift). The flexure deformation can be calculated by the ordinary method for flexure deformation, however the flexure deformation induced by the additional force should be added. The shear deformation model is based on truss mechanism, in which deformations due to elongation of diagonal strut, Δ_{s1} and shortening of diagonal strut, Δ_{s2} are considered as shown in **Fig.6**. The elongation and shortening of diagonal strut can be calculated as the deformation under the shear force, V_{s+f} (see Eq.(8)).

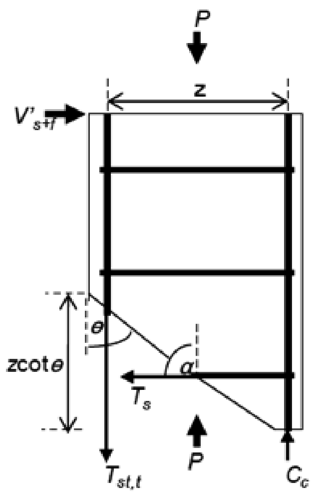


Fig.5 Effect of shear cracking on flexure deformation

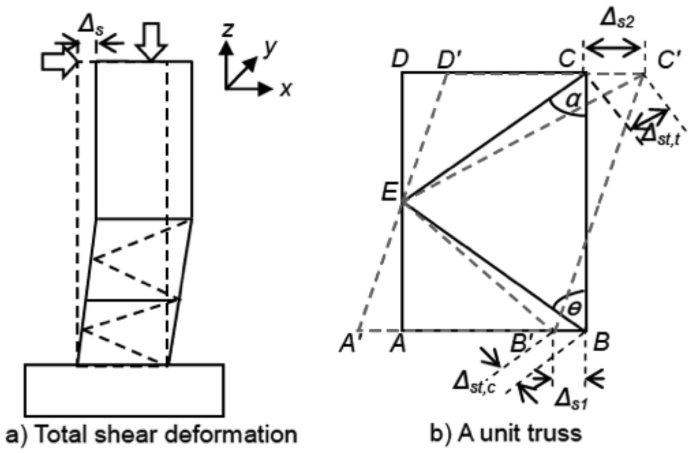


Fig.6 Shear deformation model

The model prediction results are compared with available experimental results. **Figures 7** and **8** show the prediction results for the case with steel and FRP jacket, respectively. The generic model can predict the load – deformation relationships very well for both pre- and post-peak range. The FRP tension fracture predicted by the generic model (Eq.(9)) agree well with the experimentally observed fracture. The predicted ultimate deformations for the specimens in the past experimental studies agree very well with the experimentally observed ultimate deformation as shown in **Fig.9**.

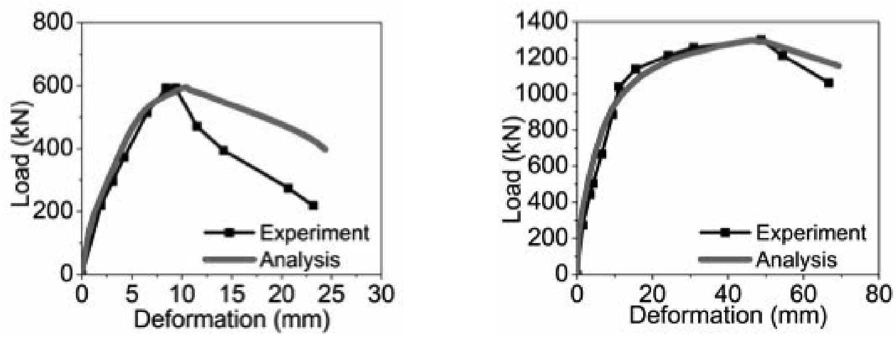


Fig.7 Prediction results for steel jacket cases

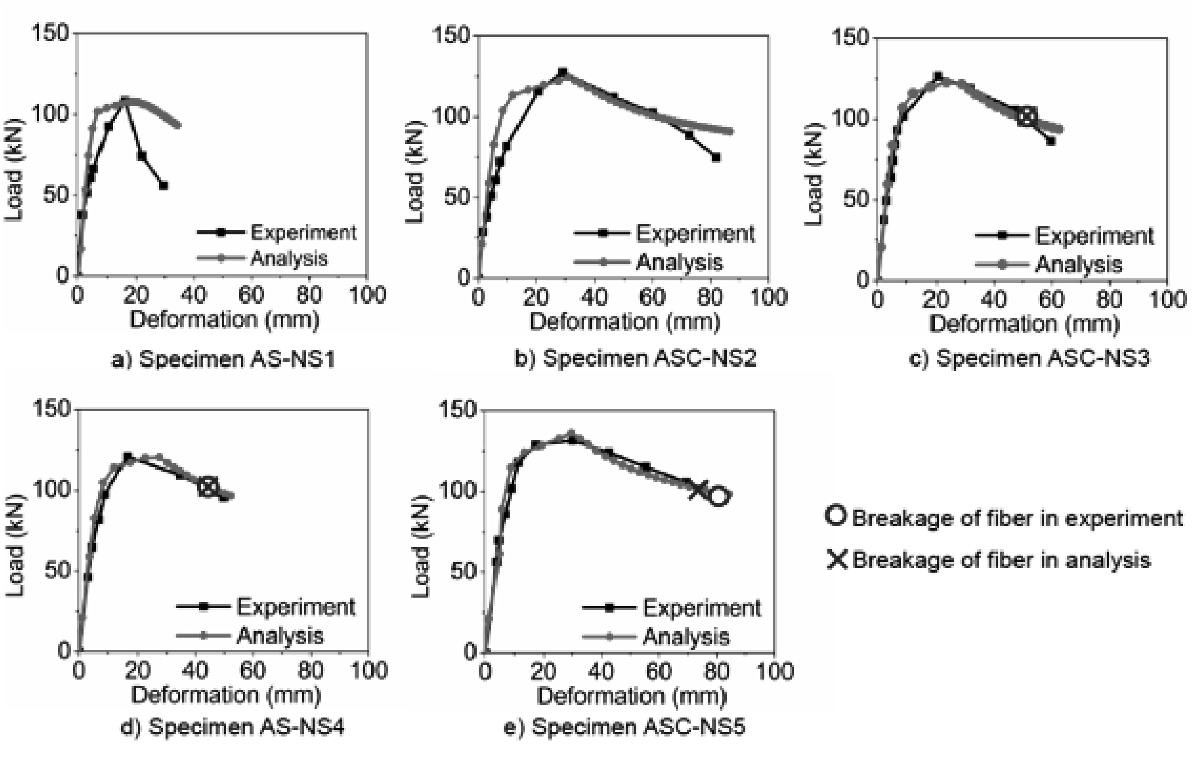


Fig.8 Prediction results for FRP jacket cases

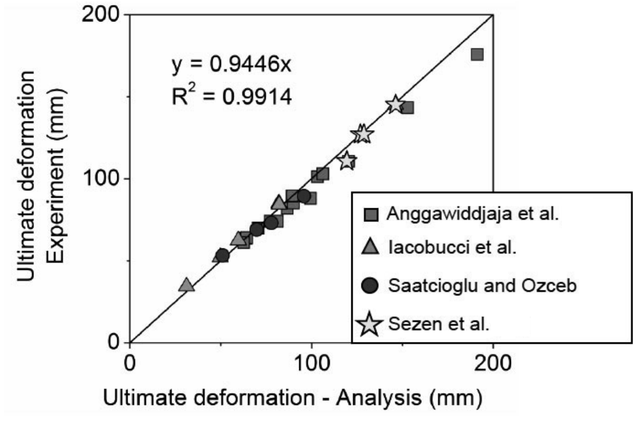


Fig.9 Comparison of ultimate deformation

3. Suitable Material Property for Shear Reinforcement/Jacket

3-1 Is high strength/stiffness always suitable property?

In order to achieve safety and serviceability, structural members need to possess required strength and stiffness. Strength and stiffness of structural materials are chosen to achieve the target member strength and stiffness. The higher strength and stiffness of material can make structural member to gain the higher member strength and stiffness. Therefore, it is quite natural to seek for structural material with higher strength and stiffness. **Figure 10** shows the stress – strain relationships of various structural materials. Steel is the most typical tension material, whose strength is lower than the other materials in **Fig.10**. This fact clearly indicates that the materials with higher strength than steel have been sought and accepted. The most successful one is carbon so far. The comparison in **Fig.10** shows a very interesting fact. The higher the strength is, the higher the stiffness is. Since steel is a unique material, which shows yielding, the stiffness here is the secant stiffness at the tension fracture. Another interesting fact is that the lower the strength is, the larger the fracturing strain is. Steel is an excellent material in terms of large fracturing strain.

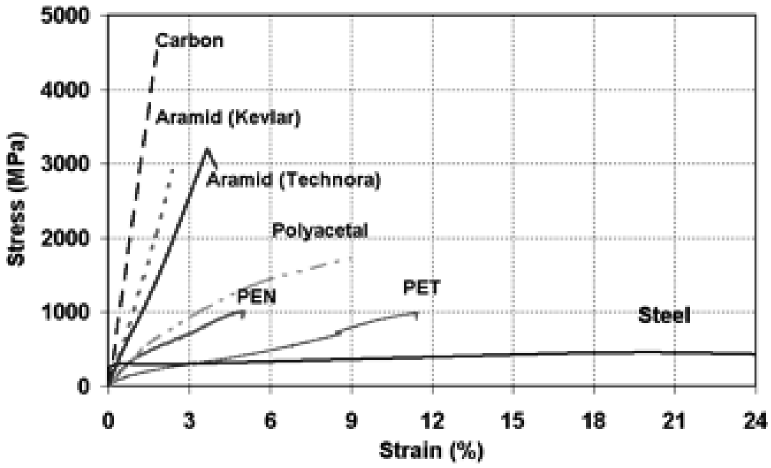


Fig.10 Comparison of stress – strain relationships of various structural materials

As the generic model in **2.2** shows, the material with higher stiffness but larger fracturing strain is a better option for shear reinforcement. From the experimental observation, the fracturing strain larger than 5% is large enough to avoid tension fracture of shear reinforcement in the post-peak range of members which show great enough ultimate deformation (high enough ductility). The higher stiffness can be achieved even by a material with lower stiffness when providing the more amount of the material. However, the larger fracturing strain cannot be achieved with a material of smaller fracturing strain. Therefore, it is practically difficult for carbon as shear reinforcement to achieve high ductility. Steel as shear reinforcement is not a good option if it yields before reaching the ultimate deformation. It is because its secant stiffness decreases quickly, resulting in a quick reduction of the remaining shear strength, which means less ductile. The best option, therefore, is the structural material with a large fracturing strain (LFS) and a moderate stiffness (see **Fig.11**). Figure 10 shows that three materials; polyacetal, polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) are examples of the materials with such a property.

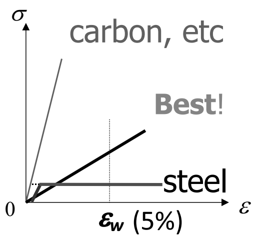
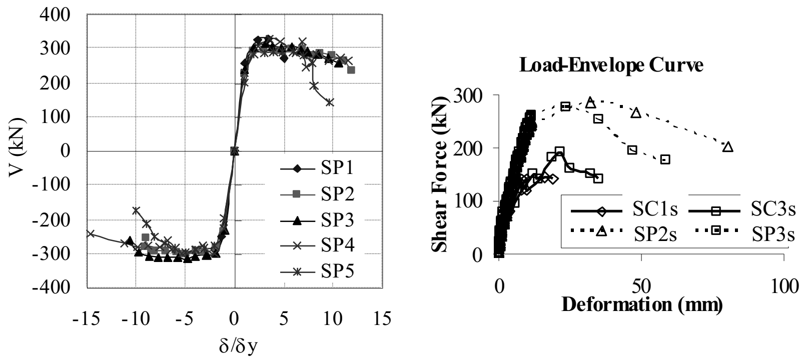


Fig.11 Best option for shear reinforcement

3-2 Member behavior with LFS shear reinforcement

There have been many studies on behavior of members with shear reinforcement whose fracturing strain is large (LFS shear reinforcement). **Figure 12** shows the deformation of column specimen with steel internal shear reinforcement and PET jacket. PET jacket does not show fracturing even after big plastic swelling deformation. The efficiency of PET jacket can be seen in both cases of specimens with high shear reinforcement ratio (flexure failure dominant case) and with small shear reinforcement ratio (shear failure dominant case) as shown in **Fig.13 (a)** and **(b)**. The specimens with PET jacket (SP1, SP2, SP3 and SP4) show greater ultimate deformation than the reference specimen without PET jacket (SP5) as shown in **Fig.13 (a)**. Comparing with the reference specimen (SC1s), which showed shear failure, in **Fig.13 (b)**, the specimen with carbon jacket (SC3s) shows greater peak load and ultimate deformation. The ultimate deformation was determined by the fracture of carbon jacket. The specimens with PET jacket (SP2s and SP3s) show much greater peak load and ultimate deformation than the specimen with carbon jacket.

Fig.12 PET jacket performance after large plastic deformation



(a) Flexure failure dominant case (b) Shear failure dominant case

Fig.13 Shear force – deformation relationships of columns with PET jacketing

The large fracturing strain of shear reinforcement is necessary only in plastic hinge zone. For the other part, commonly accepted material for jacketing, such as carbon and aramid, can be used to utilize its higher stiffness. Considering this fact, a new seismic retrofit method was developed in Japan, which is "Duplex Jacketing" (A-P Jacketing) in which PET jacket is applied to plastic hinge zone and aramid jacket is applied to the other parts (see **Fig.14**). Duplex Jacketing has been applied to real structures in Japan as shown in **Fig.15**.

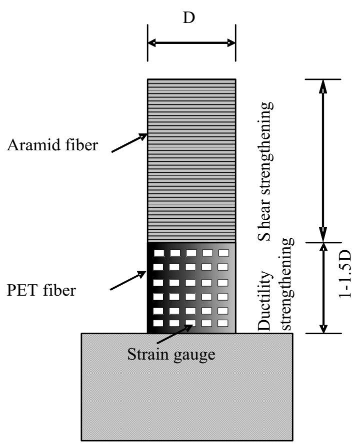
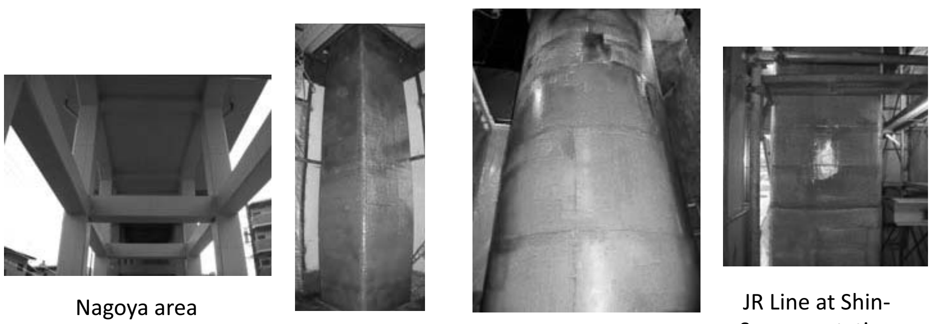


Fig.14 Duplex Jacketing



Nagoya area

Tobu Line near Tokyo

JR Line at Osaka station

JR Line at Shin-Sapporo station

Fig.15 Real applications of Duplex Jacketing

The comparison presented in **Fig.10** has a hidden fact. The higher the strength/stiffness is, the higher the cost is. Generally, the cost of material amounts necessary to achieve the same strength is less for the material with lower strength. The cost comparison between Duplex Jacketing and jacketing with aramid is shown in **Fig.16**. In order to obtain the same seismic performance, Duplex Jacketing is less expensive. The cost of jacketing with carbon is also more expensive. In case when jacketing is only necessary in plastic hinge zone, the benefit of using LFS materials is more significant.

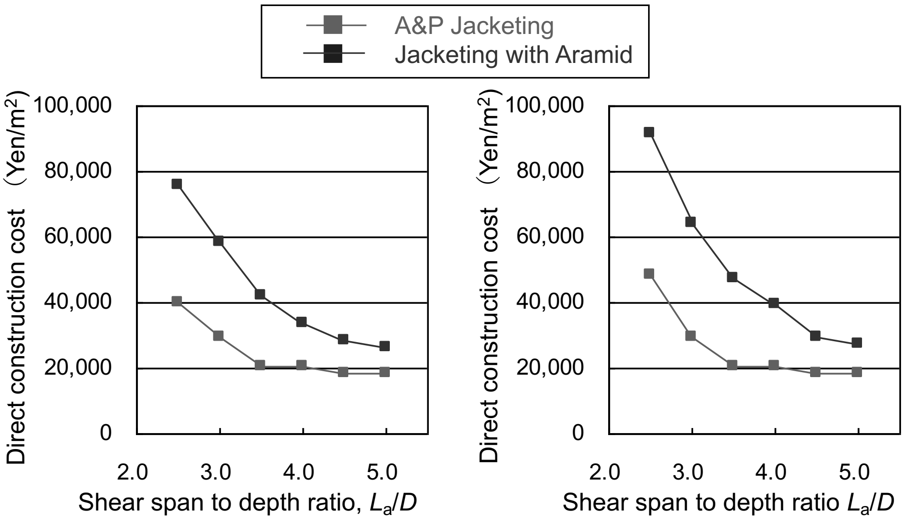


Fig.16 Cost comparison of Duplex Jacketing

4. Concluding Remarks

The generic model to predict the load – deformation relationship of concrete members reinforced with any tension material as tension and shear reinforcement, which can be either internal or external reinforcement, is presented. The generic model consists of flexure model for strength and deformation and shear model for strength and deformation. The model concept is that the load for a given deformation is the remaining flexure or shear strength, whichever is smaller. The generic model considers the interaction between flexure and shear resisting mechanisms.

Considering the prediction results by the generic model, it is concluded that the suitable material property for shear reinforcement to achieve large ultimate deformation is a large fracturing strain together with a moderate elastic modulus. The good examples of such a material are organic fiber material, such as polyacetal, polyethylene naphthalate (PEN) and polyethylene terephthalate (PET).

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