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# UNIFIED DEFINITION OF SAFETY FACTORS FOR TRADITIONAL RC MEMBERS AND MEMBERS INCORPORATING FRP

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## ABSTRACT

Due to the difference material mechanical properties of FRP with those of concrete and steel, the behaviours of members incorporated FRP are consequential different to the traditional RC members and steel members. The conventional safety theory and design method developed based on the behaviours of the traditional RC members and steel members are not suitable for the members incorporating FRP. The mechanical behaviours of the members incorporating FRP are compared with that of the traditional RC members and steel members, and the safety method is anatomized. It is pointed out that the overall safety margin of a member can be represented by strength margin, deformation margin and deformation energy margin, but the safety factor is usually represented by strength margin for the traditional RC members and steel members, which is not suitable for the members incorporated FRP. A concept of the equivalent strength safety factor $K_{eq}$ composing the overall safety margin is presented, which give unified definition of safety factors for members with different kinds of mechanical behaviours. The suggested unified definition of safety factors is applied to the design method for external bonded FRP strengthening concrete beams, FRP-concrete composite beams, concrete beams reinforced FRP bars and FRP decks, respectively. Safety design suggestions for the members incorporating FRP are pointed out.

## KEYWORDS

FRP, RC beams, safety factor, deformability, deformation energy.

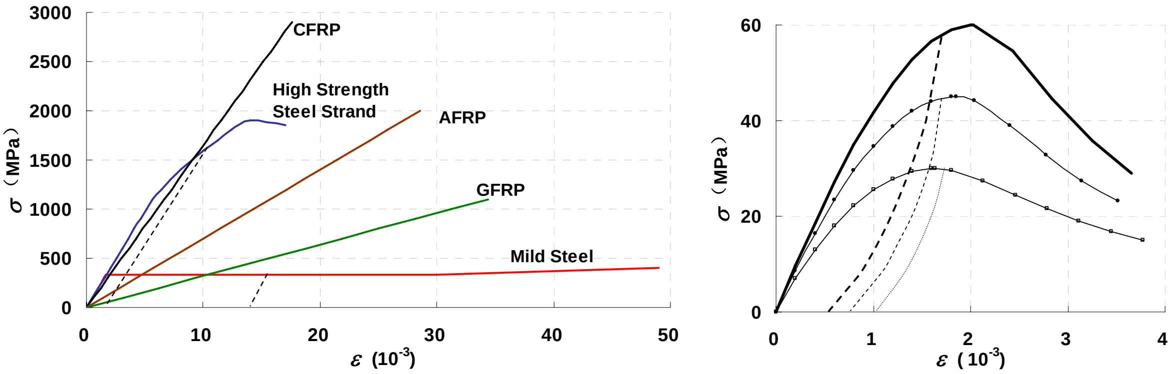
## INTRODUCTION

Fibre reinforced polymer (FRP) has been used in structures of civil engineering gradually in recent years due to its favorite properties of high-strength, light-weight and anti-corrosion. However, the mechanical behaviors of FRP of high-strength and linear elastic are very different from those of the mild steel and the concrete widely used in current structures, which have lower strength and plastic. Their stress-strain relations are shown in Figure 1, in which the dash lines are the unloading curves. The differences between mild steel and concrete with FRP are: (1) there is a yield plateau or a descending part in the stress-strain curves of steel and concrete while the curves of FRP are almost linear elastic before break; (2) steel and concrete have obvious residual deformation after unloading at the plastic part while very small residual deformation for FRP; (3) the plastic deformation is much lager than their elastic deformation at the ultimate deformation for steel and concrete while all elastic deformation and brittle failure for FRP. FRP is a distinctive structural material to steel and concrete.

Due to the difference of the materials' mechanical properties, the behaviours of members incorporated FRP, such as external bonded FRP strengthening RC members or metallic members, concrete members reinforced with FRP rebars and FRP-concrete composite members, are consequential different to the traditional RC members and steel members. Some load-deflection testing curves of members incorporating FRP in the literatures are shown in Figure 2 (Ye *et al.* 2003, Zou 2003, Feng *et al.* 2007, Li *et al.* 2006, Tavakkolizadeh and Saadatmanes 2003, Feng and Ye 2006), in which, (a), (b) and (c) show the characteristic of hardening after yielding; while (d), and (e) have no yielding, and (f) is close to linear-elastic. According the characteristic of the curves, the mechanical behaviour of members incorporating FRP can be classified two types: hardening elastic-plastic and quasi linear-elastic. It is known that RC and steel members have almost the perfect elastic-plastic mechanical behaviour, which can provide considerable plastic deformation under ultimate strength.

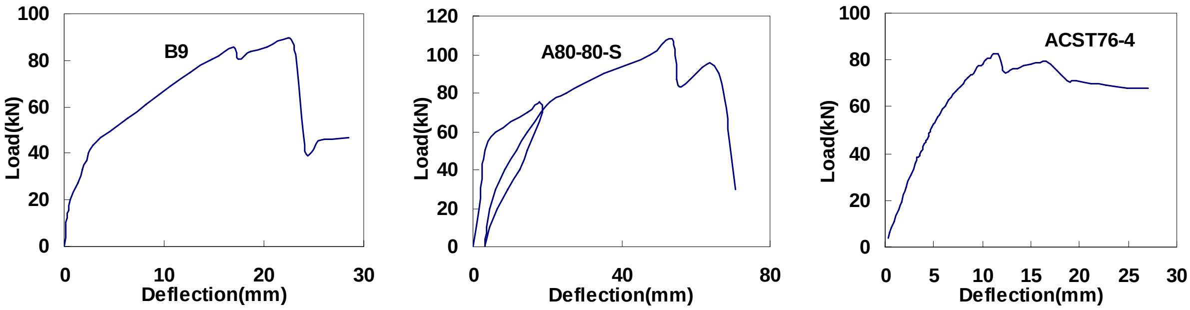
Due to reasons known, safety margin is necessary for engineering structures. The design methods of the traditional members (including RC members, members composed of steel and concrete and pure steel members) are developed based on the assumption that the members can provide sufficient plastic deformation under their strength. Thus, (1) the considerable plastic deformation may foreshow the failure of the members; (2) the plastic deformation can absorb energy so as to abate the responses by unexpected dynamic loads; (3) the plastic deformation in local may redistribute the internal forces in the indeterminate structures. Thus, the plastic deformation, i.e. ductility, is an important part of the safety margin for the RC members. As the enough ductility is indispensability for RC members, so only the strength safety factor is given for the safety margin in the existing structural design theory.

However, the members incorporating FRP have no or fewer plastic deforming capacity instead of higher strength or hardening. The conventional safety theory and design methods based on the ductile materials are not suitable for the members incorporating FRP. Therefore, the unified safety index for all kinds of members with various mechanical behaviours must be developed.

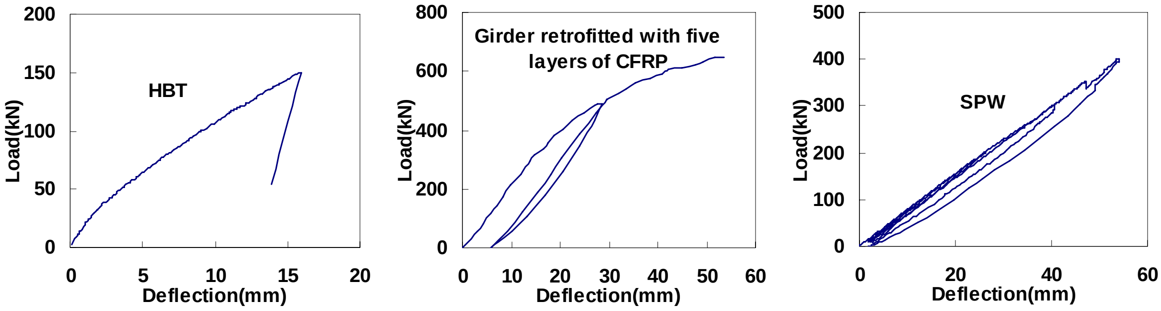


(a) Tension (b) Compressive (concrete)

Figure 1. Stress-strain relations of various structural materials



(a) FRP strengthening RC beam (b) FRP prestressing concrete beam (c) FRP reinforced aluminum beams



(d) FRP-concrete composite beam (e) FRP strengthening steel-concrete beam (f) FRP deck

Figure 2. Mechanical behaviours of various members incorporating FRP

## SAFETY MARGIN OF STRUCTURES

As we known, engineering structures must be capable to supply the necessary safety margin for the following reasons: (1) the variance of the material properties and the size of members may lead to overvalue the structural resistance; (2) the variance of the loads may beyond the loads estimated in the design; (3) the deviation of the design and structural analysis methods may depress reliability of structures. Hence, two aspects are considered to provide enough safety margin in the existing design methods. The first is to reduce the structural resistance in design as follow,

$$R_d = R_n / K_R \tag{1}$$

where, $R_d$ is the design resistance, $R_n$ is the nominal resistance which can be determined by design formula with the nominal materials' strength, and $K_R$ is the structural resistance factor which is greater than 1.0. The second aspect is to increase design load as follow,

$$U_d = K_D \cdot D + K_L \cdot L + \cdots \tag{2}$$

where $U_\mathrm{d}$ is the design load effect, $D$ is the dead load effect, $L$ is the live load effect, and $K_\mathrm{D}$ and $K_\mathrm{L}$ are the load factors for dead and live loads respectively which are greater than 1.0. In structure design, the greater factors $K_\mathrm{R}$ , $K_\mathrm{D}$ and $K_\mathrm{L}$, the less failure probability of the structures. The designed structure can be regarded as safe enough when the failure probability is considerably low.

## EXISTING STRUCTURE SAFETY INDICES

### Strength Factor

In the existing structure design methods, the following strength factor $K_\mathrm{S}$ is the primary safety index to represent the safety margin.

$$K_S = S_n / S_d \tag{3}$$

Where, $S_n$ is the nominal strength, and $S_d$ is the design strength. Here, the strength factor $K_\mathrm{S}$ includes both resistance factor $K_R$ and load factors $K_\mathrm{D}$ and $K_\mathrm{L}$.

### Ductility Factor

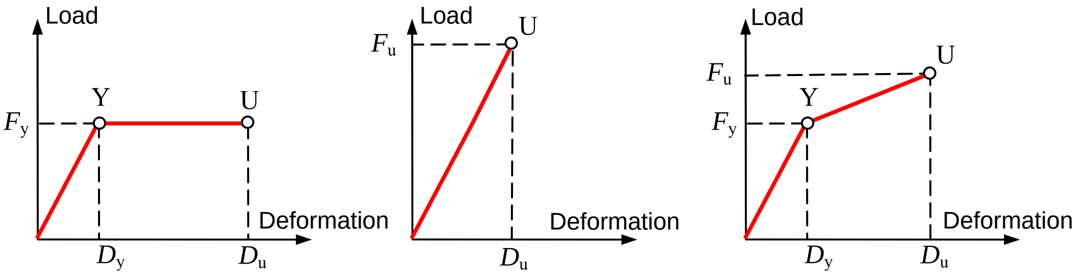
As stated previously, the traditional members have enough plastic deformation under the maximum strength. The plastic deformability, called ductility, depends on the parameters of members. The members with greater ductility should be regarded as safer than those with less ductility though their strength factors are equal. Obviously, the ductility is an important part of the safety margin. The following ductility factor as usually defined to describe the plastic deformability of members.

$$\mu = D_u / D_y \tag{4}$$

Where, $D_\mathrm{u}$ is the ultimate deformation, and $D_\mathrm{y}$ is the yield deformation. $D_\mathrm{u}$ and $D_\mathrm{y}$ may be expressed in curvatures, deflections or rotations of the members.

### Deformability Factor

Although the ductility is an important part of the safety margin, the strength factor is only used in the existing design methods for the traditional members, and the ductility factor is implicit. But when the strength factor is applied for the members incorporated FRP, the safety margin may be wrong evaluated because that the deformation capacity beyond the deformation at the design strength is not considered.



(a) Ideal elastic-plastic (b) Ideal elastic (c) Hardening elastic-plastic

Figure 3. Various load-deformation relations

The load-deformation relation of traditional members is idealized as the ideal elasto-plastic curve as shown in Figure 3(a), pure FRP members' relation without yield is idealized as elastic in Figure 3(b), and members incorporated FRP is idealized as hardening elasto-plastic in Figure 3(c). Many researchers have pointed out that the traditional strength factor for the elasto-plastic members is not used directly for the hardening elasto-plastic behavior. Abdelrahman *et al* (1995) suggested a modified ductility factor for FRP tendons prestressed concrete beams. Naaman and Jeong (1995) suggested a ductility factor considering the deformation energy. Because the different results will be obtained based on the different definition of the modified ductility factor, it can not be used as a unified safety index.

The deformability indices, presented below, were suggested by Mufti *et al* (1996) to replace ductility for FRP reinforced concrete beams.

Strength factor $S_J = M_u / M_c$ (5a)

Deformability factor $D_J = \Phi_u / \Phi_c$ (5b)

*J*-factor $J = S_J \cdot D_J = (M_u / M_c) \cdot (\Phi_u / \Phi_c)$ (5c)

Where, $M_u$ is the ultimate moment, $\Phi_u$ is the ultimate curvature; $M_c$ and $\Phi_c$ is the moment and curvature at the point of the maximum compressive s concrete train of beam is 0.001, before which the concrete can be regarded as linear elastic. Jaeger *et al* (1997) calculated these indices by tests and found that there was a corresponded relation between *J* and *c/d* (the relative compressive depth of section) both for FRP reinforced beams and RC beams. Due to that *J*-factor is the product of strength factor $S_J$ and deformability factor $D_J$ taking the design point when $\varepsilon_c$=0.001, *J*-factor is a reasonable safety index because it covers the strength safety margin and the deformation safety margin of beams. The deformability indices are adopted by Canadian Highway Bridge Design Code. It is demanded that *J*-factor should not be less than 4 for rectangular section beams and 6 for T-sections, respectively (Bakht *et al* 2000).

Similarly, Newhook *et al* (2002) defined the following deformation factor *DF*, for concrete beams reinforced with FRP bars based on the serviceability criteria of crack width.

$$DF = (M_u / M_s) \cdot (\Phi_u / \Phi_s) \tag{6}$$

Where, the $M_s$ and $\Phi_s$ represent the moment and curvature corresponding to the permissible strain $\varepsilon_{fs}$=0.002 in FRP bars, that can control the crack width. And *DF*>4 is proposed.

In the design Guideline for concrete members reinforced with FRP bars reported by ACI Committee 440 (2006), deformability factor is adopted and is defined as the ratio of energy absorption (area under the moment-curvature curve) at ultimate strength to the energy absorption at service level, which is

$$D_{\mathrm{ACI}} = E_u / E_s \tag{7}$$

However, it is not used in the design procedure and the service level is not defined clearly.

In the design Guideline for concrete members prestressed with FRP tendons reported by ACI Committee 440 (2004), following deformability index *DI* is considered in determining the safety margin,

$$DI = \frac{(1-k)}{\left(1-\dfrac{\alpha}{d\beta_1}\right)} \cdot \frac{\varepsilon_{pu}}{\varepsilon_{ps}} \tag{8}$$

The deformability index *DI* is the ratio of the ultimate curvature to the curvature under service loads at which a tensile stress in the concrete is $0.25\sqrt{f'}$ MPa.

It can be seen that the definitions of the design point of service lever determine the deformability index. Due to the different definitions of design point, the deformability index expression can be deduced. The margin between the ultimate point and the design point is defined as the safety margin in this paper. But the definition of serviceability criteria to determine the design point is not discussed in this paper. In general, the design point must be in the elastic range as the permanent damage under service load is not accepted. Because there are various behaviors of the members incorporating FRP, a unified safety factor is proposed to represent the safety margin between the ultimate point and the design point in the following parts in this paper.

## UNIFIED SAFETY FACTOR

### Design Point and Ultimate Point

A certain structure under the certain load pattern, the load-deformation curve of the structure can be acquired from initial to ultimate as illustrated in Figure 4. Design point, called point D, can be determined by the serviceability criteria and must satisfy $U_d \le R_d$, in which $U_d$ and $R_d$ are determined by Eq.1 and 2. Point U is the ultimate state of the structures.

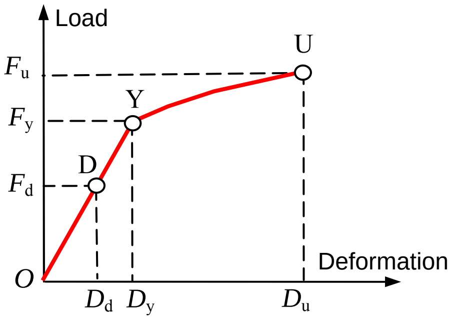


Figure 4. Load-deformation curve and characteristic points

The margin from design point D to ultimate point U is safety margin. It can be seen the margin includes strength, deformation and deformation energy. There are four factors are defined, as follows

Strength safety factor $$K_F = F_u / F_d \tag{9}$$
Deformability safety factor $$K_D = D_u / D_d \tag{10}$$
Energy safety factor $$K_E = E_u / E_d \tag{11}$$
Modified *J*-factor $$K_J = K_F \cdot K_D \tag{12}$$

The strength safety factor provide the capacity bearing overload, deformability safety factor is to ensure sufficient deformation warning before failure, and energy safety factor performs the overall safety margin of the structure. For the traditional members with the ideal elastic-plastic behaviours, only the strength safety factor $K_F$ is adopted because the inherent deformability margin and energy margin are suffice in the most cases. For the linear elastic members, $K_D$=$K_F$ and $K_E$=$K_J$=$K_D^2$, so also only $K_F$ is adopted. However, for the members incorporating with FRP, the situations between the ideal elastic-plastic and the linear elastic, the strength safety factor $K_F$ will not enough to represent the whole safety margin because of the complicated relation among $K_F$, $K_D$ and $K_E$. Although Energy safety factor $K_E$ can represent the whole safety margin, it is not convenience for practical application in structure design.

## Composition of Safety Margin: Basic and Additional

For the traditional members, the yielding strength $F_y$ is equal to the ultimate strength $F_u$ if the ideal elastic-plastic behaviours is assumed. Thus, the strength safety factor can be expressed as,

$$K_F = F_u / F_d = F_y / F_d \tag{13}$$

It will be known from above relation that the structure will not yield and no damage under expected overloads. The deformability safety factor $K_D$ for elastic-plastic members, although it is usually not used but ensured to cover for unexpected overloads. Hence, the safety margin between the yield point Y and the design point D can be regard as a basic safety margin for the structure whatever it is elastic-plastic or hardening elasto-plastic. And the safety margin between ultimate strength point U and the yield point Y can be regard as additional safety margin, which is need for unexpected overloads and to ensure sufficient failure warning. For traditional members, the additional safety margin provided by the sufficient ductility can be acquired by the conceptual design and the detailing. Therefore, the safety margin of structures can be divided into two parts as illustrated in Figure 5. Based the definition of the basic safety margin, a basic strength factor $K_0$ is defined as

$$K_0 = F_y / F_d \tag{14}$$

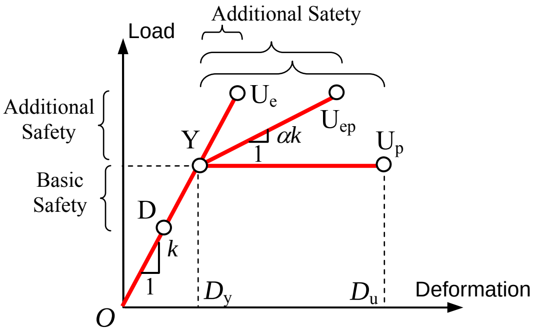


Figure 5. Composition of safety storage

## Equivalent Strength Factor

The overall safety margin of a member should contain strength, deformation and energy margin between the ultimate point D and the design point U as shown in Figure 5. Due to the strength factor is the accustomed expression form of structural safety margin in the existing design methods, following equivalent strength factor $K_{eq}$ is proposed to represent the overall safety s margin of a member.

$$K_{eq} = K_E / K_D = (E_u / E_d)/(D_u / D_d) \tag{15}$$

The equivalent strength factor $K_{eq}$ is named for the reason that the dimension of energy divided by deformation is the unit of force. For the ideal elastic members, the equivalent strength factor is same as the strength factor, $K_{eq}$=$K_F$. For members incorporating FRP with strength hardening elastic-plastic load-deformation relation as shown in Figure 5 and based on above definition, $K_{eq}$ can be drawn as,

$$K_{eq} = \frac{2K_0K_D - K_0^2 + \alpha(K_D - K_0)^2}{K_D} \tag{16}$$

where, $\alpha$ is the ratio of the stiffness of the strength hardening line after yield point Y to the elastic stiffness $k$ before yielding, and $\alpha$=0 for ideal elastic-plastic model and $\alpha$= 1.0 for ideal elastic model. Thus, the equivalent strength factor of all kind of members can be calculated easily when their behaviour are approximately modelled by a bilinear load-deformation relation in Figure 5.

Obviously, $K_{eq}$ equivalent strength factor can represent the strength, deformation and energy margin. And also $K_{eq}$ contains basic strength factor $K_0$ and additional strength factor. So $K_{eq}$ can estimate the safety margin of structure comprehensively. A permission of $K_{eq}$ greater than a certain value should be taken for all members while the basic safety storage is satisfied. The difference between $K_{eq}$ and $K_0$ represents the additional safety margin to against the unpredictable overloads.

## VALUE OF $K_0$ AND $K_{eq}$

According to ACI committee 318(2005), the load factors $K_D=K_L=1.4$ in item 9.2 generally, and strength reduction factor $\phi=1/K_R=0.9$ for the ductile members and $\phi=1/K_R=0.65$ for the brittle members. If the ductile member is modelled as the ideal elastic-plastic, $K_0$ can be determined as 1.4/0.9=1.55; if the brittle member is modelled as the ideal elastic, $K_{eq}=K_F$ can be determined as 1.4/0.65=2.15, which is close to 2.0, the strength safety factor for the linear elastic structures. It shows that the RC members and linear elastic members have the approximate same safety margins in terms of the equivalent strength factor $K_{eq}$. So based on the safety margin used for traditional RC members in the existing design method, $K_0 \geq 1.55$ and $K_{eq} \geq 2.15$ are suggested.

If the ductile member is modelled as the ideal elastic-plastic member with hardening ratio $\alpha=0$ and $K_{eq}=2.15$, $K_0=1.55$, then $K_D=2.53$ based on Eq.16. Furthermore, the ductility factor $\mu=1.63$. This should be the lower bound limit of the ductility factor for ductile members. In general, RC member with proper design is more ductile. When $K_0=1.55$ and $K_D=2.53$ are used for the ductile RC member, the Modified *J*-factor $K_J=3.92$ according to Eq.12; whlie $K_{eq}=K_F=K_D=2.15$ for the brittle over-reinforced member, $K_J=4.62$. It is shown that the permission of $K_{eq}$ and $K_F$ and the permission of the *J*-factor suggested by Mufti *et al* (1996) and Jaeger *et al* (1997) are approximately consistent. These mean that this criterion is reasonable for RC members.

Therefore, the equivalent strength safety factor $K_{eq}$ and the basic strength safety factor $K_0$ are proposed as the unified factors to evaluate the safety margin of various members with the different mechanical behaviours, especially for RC members and members incorporating FRP. The members with the equal $K_{eq}$ can be regarded with the same safety margin, and $K_0$ can be same as the strength factor of traditional RC members to prevent yielding and damage under the normal predictable loads. According the standard of ACI, $K_0 \geq 1.55$ and $K_{eq} \geq 2.15$ is proposed for the common building structural members.

## APPLICATIONS OF $K_{eq}$

### External Bonded FRP Sheets Strengthening RC Beams

A series of RC beams, as shown in Figure 6, strengthened with external bonded FRP sheets are studied to explain the application of the equivalent strength factor $K_{eq}$. The section of the RC beams is 200×150mm and the original steel rebar ratio is 0.5%. The thickness of the external bonded FRP sheets are changed from 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2mm. The load-deflection curves of the beams were obtained by finite element analysis as shown in Figure 7(a), in which all failure modes including concrete crush, FRP rupture and debonding are considered. Their loads and deflections at the ultimate and yield point are listed in Table 1.

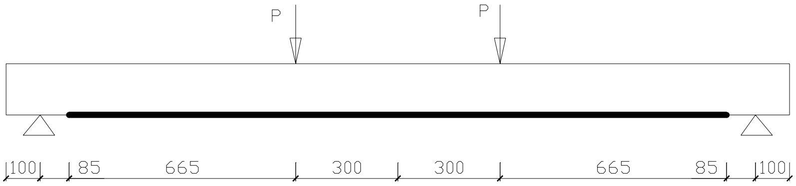


Figure 6. A FRP strengthening RC beam

Taking the basic strength factor $K_0=1.55$, the design point can be determined based on the strength and deformation at yield point. Then, the equivalent strength factor $K_{eq}$ for each beam is calculated as listed in Table 1 and Figure 7(a). It can be found that $K_{eq}$ is less than 2.15 and $K_J$ is less than 4.0 for the member with maximum FRP thickness 1.2mm due to over-reinforced and lack of deformability. So the safety margin is insufficient. This result means that the amount of FRP should not be increased only focus on the strength enhancement.

On the other hand, in the existing design suggestion for FRP strengthening RC beams, the ultimate point is usually adopted to satisfy the strength safety. If the FRP strengthening RC beams been designed in this way and taking the total strength factor 1.55 that is the strength factor for traditional RC members, the strength at design point will be $F_d=F_u/1.55$. Thus, the safety margins of the design beams are shown in Table 2 and Figure 7(b). It can be seen that all the strengthened members can not obtain the sufficient safety margin as their $K_{eq}<2.15$. Besides that, the basic strength factor $K_0$ of the beams are range from 1.09 to 1.41, which means that the members may yield under the predicable design overloads. It is shown that the traditional design method based on the ultimate state is not suitable for the members incorporating FRP. In this case, No.2 member with 0.2 mm

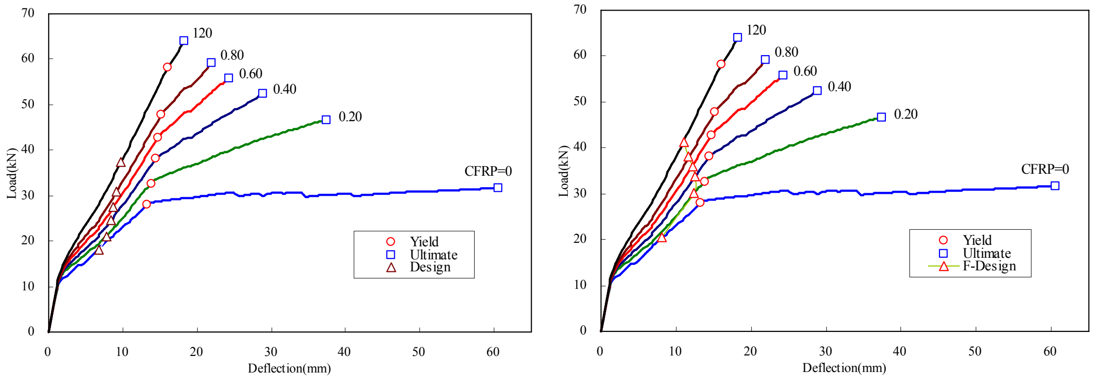
FRP thickness has the greatest $K_J$ of 4.65 but the least $K_0$ of 1.09. It shows that the deformability factor $K_J$ may not cover the different safety demands.

Table 1. Safety Margin Analysis of FRP strengthening RC beams when the design points are determined based on the yield points taking $K_0$=1.55

| No. | Thickness of FRP sheets (mm) | Ultimate Point | | Yield Point | | Design Point | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $F_u$ (kN) | $D_u$ (mm) | $F_y$ (kN) | $D_y$ (mm) | $F_d$ (kN) | $D_d$ (mm) | $\alpha$ | $\mu$ | $K_D$ | $K_{eq}$ | $K_J$ |
| 1 | 0.0 | 31.68 | 60.55 | 28.04 | 13.32 | 18.09 | 6.71 | 0.04 | 4.55 | 9.02 | 3.06 | 15.80 |
| 2 | 0.2 | 46.59 | 37.39 | 32.69 | 13.87 | 21.09 | 7.81 | 0.25 | 2.70 | 4.79 | 3.15 | 10.57 |
| 3 | 0.4 | 52.34 | 28.96 | 38.10 | 14.42 | 24.58 | 8.36 | 0.37 | 2.01 | 3.46 | 2.80 | 7.38 |
| 4 | 0.6 | 55.77 | 24.32 | 42.68 | 14.70 | 27.53 | 8.64 | 0.47 | 1.65 | 2.81 | 2.51 | 5.70 |
| 5 | 0.8 | 59.03 | 21.90 | 47.90 | 15.25 | 30.90 | 9.19 | 0.53 | 1.44 | 2.38 | 2.24 | 4.55 |
| 6 | 1.2 | 63.88 | 18.31 | 58.08 | 16.08 | 37.47 | 9.74 | 0.72 | 1.14 | 1.88 | 1.86 | 3.20 |

Table 2. Safety Margin Analysis of FRP strengthening RC beam when the design points are determined based on the ultimate points taking the total strength factor 1.55

| No. | Thickness of FRP sheets mm) | Ultimate Point | | Yield Point | | Design Point | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $F_u$ (kN) | $D_u$ (mm) | $F_y$ (kN) | $D_y$ (mm) | $F_d$ (kN) | $D_d$ (mm) | $\alpha$ | $F_y/F_d$ | $K_{eq}$ | $K_J$ |
| 1 | 0.0 | 31.68 | 60.55 | 28.04 | 13.32 | 20.44 | 8.09 | 0.04 | 1.37 | 2.69 | 11.60 |
| 2 | 0.2 | 46.59 | 37.39 | 32.69 | 13.87 | 30.06 | 12.45 | 0.25 | 1.09 | 2.09 | 4.65 |
| 3 | 0.4 | 52.34 | 28.96 | 38.10 | 14.42 | 33.77 | 12.50 | 0.37 | 1.13 | 1.93 | 3.59 |
| 4 | 0.6 | 55.77 | 24.32 | 42.68 | 14.70 | 35.98 | 12.20 | 0.47 | 1.19 | 1.82 | 3.09 |
| 5 | 0.8 | 59.03 | 21.90 | 47.90 | 15.25 | 38.08 | 11.70 | 0.53 | 1.25 | 1.78 | 2.90 |
| 6 | 1.2 | 63.88 | 18.31 | 58.08 | 16.08 | 41.21 | 11.08 | 0.72 | 1.41 | 1.64 | 2.56 |



(a) yield points as nominal design points (b) ultimate points as nominal design points

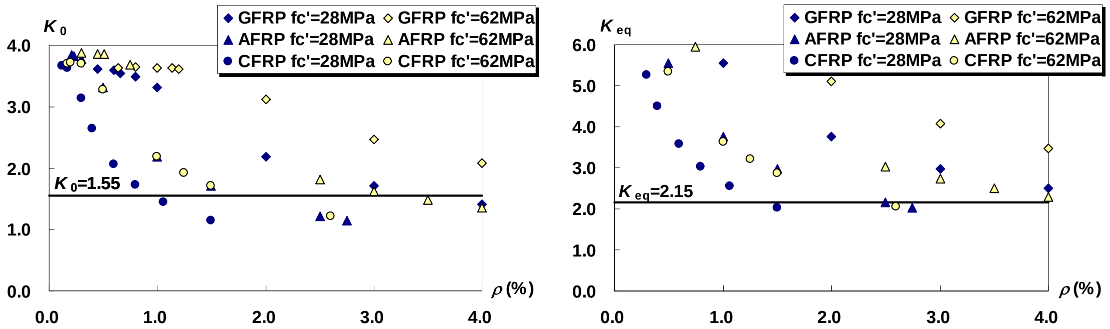
Figure 7. Resistance curves of FRP strengthening RC beams

## FRP Bar Reinforced Concrete Beams

There is not obvious yield point on the load-deformation curve of FRP bar reinforced concrete beams. The strength reduction index $\phi$ is multiplied to the ultimate resistance $M_u$ to get the design strength in ACI design guideline (ACI Committee 440, 2006), where

$$\phi = \begin{cases} 0.55 & \rho_f \le \rho_{fb} \\ 0.3 + 0.25\dfrac{\rho_f}{\rho_{fb}} & \rho_{fb} < \rho_f < 1.4\rho_{fb} \\ 0.65 & \rho_f \ge 1.4\rho_{fb} \end{cases} \qquad (17)$$

Actually，the design strength $\phi M_u$ is the nominal yield strength because the FRP bar reinforced concrete beam is always controlled by the serviceable criteria. So the key points for FRP bar reinforced concrete beam can be obtain as follows: (1) the ultimate point is calculated by ultimate state analysis or test; (2) the nominal yield strength is determined by $\phi M_u$ and find the corresponding deformation on the load-deformation curves; (3) the design point is determined by the the serviceable criteria including deflection and crack width. Thus, the safety margin can be calculated by the proposed safety factors.



(a) Basic resistance safety factor (b) Equivalent resistance safety factor

Figure 8. Safety storage factors of FRP strengthening RC beams

Newhook *et al* (2002) designed and analyzed six groups of 48 FRP bar reinforced concrete beams, and got their ultimate moments $M_u$ and curvatures $\Phi_u$. Then the nominal yield strengths are determined at the points of moment $M_y=\phi M_u$. And the design points of the beams were obtained based on controlling the width of cracks by limiting the tensile stress in the FRP bar. Thus, the basic strength factor $K_0$ and the equivalent strength factor $K_{eq}$ can be obtained based on the Eq.14 and Eq.16, as shown in Figure 8.

It can be seen that most members are satisfied the condition of $K_0\geq1.55$ and $K_{eq}\geq2.15$ except for eight members with lower $K_0$ and four of eight with lower $K_{eq}$. The unsatisfied members have the higher reinforcement ratio than the others in same group. Though it is believed that all members can exhibit large deformation before failure as their DF≥4.0, the basic strength factor of some member is too low obviously. The minimum $K_0$ is 1.15, while its $K_F$ is 1.76 and $K_D$ is 2.24 only. It has much lower safety margin than the traditional RC members. For these members controlled by the strength, the safety margin should be checked again.

### FRP-Concrete Composite Beams

There is not obvious yield point on the load-deformation curve of FRP-concrete composite beams, as shown in Figure 2(d). It is believed that the design point of FRP-concrete composite beam is always controlled by the serviceable criteria of the deflection. As there is not approved design guide for composite beams yet, the ultimate point and the design point are suggested as: (1) the ultimate point is calculated by ultimate state analysis or test; (2) the design point is determined by the the serviceable criteria of the deflection. Thus, the equivalent strength safety factor $K_{eq}$ can be calculated.

Table 3. Safety margin analysis of FRP-concrete composite beams

| References | No. | Span (m) | Design Point | | Ultimate Point | | $K_D$ | $K_{eq}$ | Failure mode |
|---|---|---|---|---|---|---|---|---|---|
| | | | Load (kN) | Deflection (mm) | Load (kN) | Deflection (mm) | | | |
| Li *et al* (2006) | HBT | 2.1 | 82.2 | 7.00 | 149.6 | 16.00 | 2.29 | 2.02 | FRP shear failure |
| | HBR | 2.1 | 49.3 | 7.00 | 94.6 | 15.10 | 2.16 | 2.03 | FRP shear failure |
| | HB | 2.1 | 44.1 | 7.00 | 99.2 | 18.90 | 2.70 | 2.42 | FRP shear failure |
| Li (2007) | HB1 | 2.8 | 77.1 | 9.33 | 165.8 | 23.41 | 2.51 | 2.29 | Concrete crush |
| | HB2 | 2.8 | 100.2 | 9.33 | 287.6 | 33.00 | 3.54 | 3.06 | Interface failure |
| | HB3 | 2.8 | 137.9 | 9.33 | 147.3 | 10.92 | 1.17 | 1.16 | Interface failure |
| Nordin and Taljsten (2004) | BeamB | 2.7 | 98.1 | 9.00 | 278.2 | 26.50 | 2.94 | 2.87 | Concrete crush |
| | BeamC | 2.7 | 134.0 | 9.00 | 292.7 | 23.60 | 2.62 | 2.35 | Concrete shear failure |
| Hulatt *et al* (2004) | Beam2 | 1.5 | 19.2 | 5.00 | 40.2 | 13.20 | 2.64 | 2.30 | - |
| | Beam4 | 1.5 | 20.0 | 5.00 | 30.3 | 8.78 | 1.76 | 1.65 | - |
| | Beam6 | 1.5 | 24.1 | 5.00 | 42.1 | 9.85 | 1.97 | 1.86 | - |
| | Beam7 | 1.5 | 25.8 | 5.00 | 51.8 | 17.30 | 3.46 | 2.43 | - |
| Branco *et al* (2003) | | 4.0 | 24.9 | 13.33 | 95.8 | 182.00 | 13.65 | 4.57 | FRP shear failure |

In general, the deflection limit of beam for building structure is 1/250~1/300 span，and 1/500~1/800 span for bridges. Here, 1/300 span the deflection limit is taken to analyze some tested FRP-concrete composite beams in the references. The parameters and the results are listed in Table 3. The results show that there are five members not satisfied $K_{eq} \geq 2.15$. Therefore, it is proposed that the both the strength and the deformation control are necessary for the design of the FRP-concrete composite beams.

### FRP Decks

Pure FRP members show almost linear elastic behaviour with high strength and low stiffness, so they are always controlled by the deflection limit. Similar to FRP-concrete composite beams, the ultimate point and the design point can be determined so that $K_{eq}$ can be calculated. 1/300 span as the limit is taken to analyze some tested FRP decks in references, as shown in Table 4. The results show that there is only one members not satisfied $K_{eq} \geq 2.15$, which was manufactured in poor quality. The average $K_{eq}$ of all members is 4.68. So these members have much more safety margin than traditional RC members when the serviceable criterion of deflection ≤1/300 span is used. Therefore, it is proved that the deflection control the FRP deck design.

Table 4. Safety storage analysis of FRP decks

| References | No. | Span (m) | Design Point | | Ultimate Point | | $K_D$ | $K_{eq}$ | Load pattern | Failure mode |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Load (kN) | Deflection (mm) | Load (kN) | Deflection (mm) | | | | |
| Feng and Ye (2006) | SP | 1.3 | 14.6 | 4.33 | 81.0 | 24.13 | 5.57 | 5.55 | 3-point | Delaminating |
| | SPW | 1.3 | 16.4 | 4.33 | 128.5 | 33.40 | 7.71 | 7.83 | 3-point | Web shear |
| | FD | 1.3 | 138.2 | 4.33 | 256.0 | 8.78 | 2.03 | 1.94 | Wheel | Debonding |
| | FDW | 1.3 | 127.2 | 4.33 | 276.0 | 11.2 | 2.58 | 2.33 | Wheel | Web shear |
| | HD0 | 2.8 | 154.1 | 9.33 | 485.5 | 30.6 | 3.28 | 3.19 | Wheel | Debonding |
| | HDW3 | 2.8 | 135.5 | 9.33 | 611.6 | 46.1 | 4.94 | 4.60 | Wheel | Punching |
| | HDW5 | 2.8 | 217.5 | 9.33 | 1720 | 91.2 | 9.77 | 8.10 | 4-point | Rupture |
| Keller and Schollmayer (2004) | | 2.7 | 130.2 | 9.00 | 795.3 | 61.9 | 6.88 | 6.22 | Wheel | Delaminating |
| Hayes *et al* (2000) | | 1.22 | 82.4 | 4.07 | 369.0 | 27.6 | 6.79 | 4.82 | Wheel | Punching |
| Williams *et al* (2003) | F7-1 | 3000 | 163.0 | 10.00 | 530.8 | 45.1 | 4.51 | 3.53 | Wheel | Debonding |
| | F7-2 | 3000 | 177.8 | 10.00 | 584.1 | 38.0 | 3.80 | 3.42 | Wheel | Delaminating |

## CONCLUSIONS

(1)The mechanical behaviour of members incorporating FRP is much different with traditional RC and steel members with the approximate ideal elastic-plastic behaviour. The safety design method for traditional members can not be applied for the members incorporating FRP.

(2) The whole safety margin of structures are composed of strength safety margin, deformability safety margin and deformation energy safety margin. The corresponding safety factors are presented.

(3) An equivalent strength safety factor $K_{eq}$, which is obtained by using the ratio of deformation energy safety margin to deformability safety margin, is suggested to represent the unified safety factor for different mechanical behaviours of members.

(4) Based on the understanding that the structure must not be yield under predicable overload and failure under unpredictable overload, the safety margin is suggested to divide into two aspects: the basic safety margin and the additional safety margin. Thus, the whole safety margin of different members can be evaluated by the equivalent strength safety factor $K_{eq}$ and the basic safety factor $K_0$.

(5) Based on the suggestion of the unified safety factor, the design method and safety of several kinds of members incorporating FRP are analyzed, and some suggestions for their design are made.

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