

Philosophy of Conservativeness in FRP-based Structural Strengthening Design

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Abstract— Fibre reinforced polymer (FRP) composites are regarded as the Advanced Composites in the construction industry due to their high potential and significant advantages in tackling the modern infrastructural problems and requirements. In particular, they are widely used as externally-bonded reinforcement system for strengthening of existing structures. However, FRP-composites lack in time-testimony for construction applications. Furthermore, particularly as an externally-bonded reinforcement, they exhibit an array of distinctive and contrasting characteristics and behavior. Apparently, the FRP-based strengthening design guidelines tend to absorb these peculiarities through imparting more than usual conservativeness in the design process. This paper aims at providing the conceptual description of conservativeness hypothesis pertinent to FRP-based structural strengthening design. The specific intention is to provoke stimulation amongst the engineers by providing a bigger picture behind the FRP-based strengthening.

Index Terms—Fibre reinforced polymer (FRP) composites, Strengthening, Conservativeness.

I. INTRODUCTION

THE two world-wars have left the humankind with drastic embarrassments, losses and a deep sense of frailty. Despite of many ill effects, never the less, they have given ample opportunities to us to genuinely reconsider and improve the undesired impacts of the traditionalisms that affect the sustainability of life. As a result, many modern inventions find their roots directly or indirectly linked to the needs generated in the pre- and post-world war periods. One of these needs is to be lighter yet tough in the manufacturing of military (and commercial) aircrafts, naval vessels and automobiles. Traditionally, these structures were built largely of metallic materials and alloys. The material scientists of mid-20th century were compelled to develop alternative resorts to these conventional materials. Such needs, along with the simultaneous advances in polymer science and chemistry have led to the emergence of polymeric materials that have shown incredibly high strength-to-weight ratios and apparent sturdiness against corrosion-based degradations [1]. In the post-world war period, such polymeric materials have played a key-catalyst role in the industrial and economic growths by revolutionising the way things are made. These polymeric materials, technically called the fibre reinforced polymer (FRP) composites, are believed to be one of the very important material innovations of the century and affect almost everything we use today – from pens to computers and from school bags to satellites. The aerospace, naval and

automobile industries have significantly nurtured the growth of these materials so much so that by the late 1970's the world polymer production outdid that of steel [2]. It was only after this the Civil Engineers started focusing efforts on exploiting the potential of FRP-composites for construction applications by bringing them into the mainstream practice. Consequently, many demonstrative civil engineering applications of FRP-composites have started emerging in the 1980's. Since then, the dedicated efforts of almost 3 decades towards establishing FRP-composites as a reliable structural material for construction industry have elevated them today to the status of *advanced composites* in construction. Most important FRP-applications in construction industry involve using them either as an internal reinforcement (as an alternate to the conventional steel reinforcement for new constructions) or as an externally-bonded reinforcement (to existing structural elements for strengthening or retrofitting). The latter, however, is more popular than the former due to the following advantages:

1. Their availability as the high quality factory-made products and as the made-in-situ products produced with relative ease.
2. The possibility of tailoring their shape and size to suit site-specific conditions.
3. A wide range of selection of qualitative and mechanical properties (based on constitutive fibre and resin types, and their relative proportions) to meet structure-specific requirements.
4. Less messy and less time and resources consuming applications.

FRP-composites have been effectively used as an externally-bonded reinforcement for flexural and shear strengthening of flexural members and confinement-based axial strengthening of compression members. Many guidelines [3–6] have emerged in last decade for FRP-based structural strengthening design. However, FRP-composites are relatively new in construction industry compared to the established structural materials such as concrete, steel and timber and hence carry *lack of time-testimony* [7]. Additionally, externally-bonded FRP reinforcements exhibit an array of distinctive and contrasting characteristics. These factors lead to reduced confidence on their load-response and long-term behavior. The strengthening design solutions with externally-bonded FRP reinforcements still have to contain

safety and reliability comparable to that prevalently prescribed in conventional structural designs. Towards this end, the design guidelines for FRP-based strengthening tend to be more conservative than usual [8]. However, the means of imparting conservativeness within strengthening design process are not yet fully understood. The type, nature and extent of uncertainties involved in the design process for *strength* (for new constructions) and that for *additional strength* (for strengthening existing structures) are substantially different. Still, the safety formats used in FRP-based strengthening remain largely cloned from that for design for new construction. The next decade is highly likely to witness major changes in the FRP-based strengthening design criteria, with some of the design guidelines upgraded to be the design standards. It is important at this juncture to thoroughly comprehend the safety format used in FRP-based strengthening in order to ensure safety and reliability in a rational manner. This paper presents a conceptual discussion on the philosophy behind the conservativeness hypothesis in FRP-based structural strengthening design.

II. THE CONSERVATIVENESS HYPOTHESIS

Conservativeness is probably a very frequently used term in the civil engineering design. In spite of the fact that it is not fully descriptive or prescriptive, we still substantially rely on it as it keeps us on the safer side. Most engineering design processes tend to be conservative in order to be safe. Structural engineering design process typically involves estimations of the load effect and resistance for a structural element. Fig. 1 conceptually shows that the conservativeness gets associated with the design through resistance estimation and load effect estimation while setting the corresponding margins between the nominal and the design values of resistance and load effect. The design values of the resistance and load effects provide a means to work out strength limit-state using which the indicators of the safety-content, such as the margin of safety (in deterministic domain), and probability of failure or reliability index (in probabilistic domain), can be determined. Typically, the design standards prescribe the design criteria such that the safety-content of the resultant design solutions is equal to or greater than a pre-set target value of one of these safety indicators. Thus, in a typical structural design process, the conservativeness associated with the load effect and resistance estimations are directly related to the required safety-content, and as evident from Fig. 1 that the conservativeness in either of these two estimations is a *subset* of safety-content. For the strengthening problems, the conservativeness in the load effects estimation, generally, is a constraint to be obliged and hence the only component available in hand to achieve the required safety-content is the conservativeness in the resistance estimation. The focus of this study is, therefore, predominantly on the conservativeness associated with the resistance contribution of the FRP component. Fig. 2 conceptually shows the relation between conservativeness associated with the resistance contribution of the FRP component and the safety-content of the strengthened

structural element. The fact to highlight here is that the safety-contents in the pre-strengthened condition (with non-augmented load demand) and post-strengthened condition (with augmented load demand), ignoring the time-dependent degradations in both the conditions, can be different. It is likely that the revised safety-content for the latter condition is smaller than that for the former condition. For FRP-based structural strengthening in particular, the post-strengthened safety-content (in terms of reliability index) is expected to be lesser than that for a new replacement [7]. This can be due the reason that the uncertainties involved in design for new constructions and that for strengthening existing structures are different. Next section provides a discussion on uncertainties in FRP-based strengthening design.

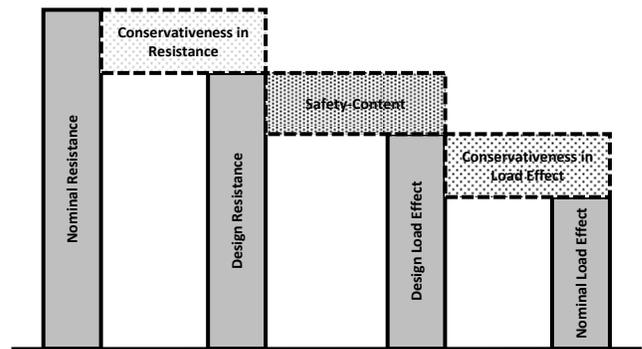


Fig. 1 Conservativeness Hypothesis in Structural Design

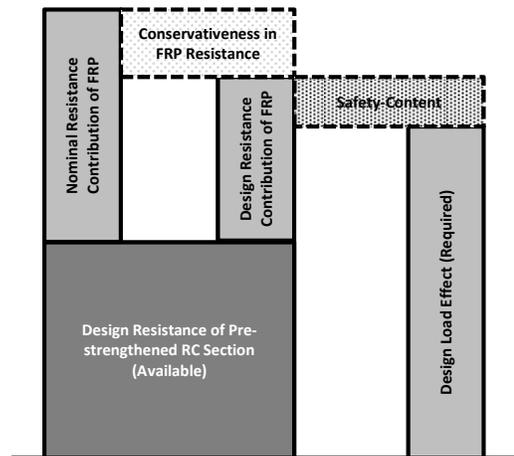


Fig. 2 Conservativeness Hypothesis in Strengthening Design

III. UNCERTAINTIES IN FRP-BASED STRENGTHENING DESIGN

The safety formats in any design guideline or standard are calibrated primarily to account for the possible uncertainties and their implications. For FRP-based structural strengthening designs, the uncertainties can be broadly grouped into *Constitutive Uncertainties* and *Behavioral Uncertainties* [9], which are discussed below:

1) Constitutive Uncertainties

The mechanical properties of the FRP composites, such as the rupture strain, the modulus of elasticity and the tensile

strength, inherently carry uncertainties within them [9, 10]. Since the constitutive relationship of FRP composites is invariably the function of their mechanical properties, such uncertainties are called the *constitutive uncertainties*. The most common type of constitutive uncertainties is the variability, which can either be *random*, *phenomenon-reliant* or *process-reliant*.

The *random variability* is attributed to the local variations in the quality controls and conditions during the production. It exists even on employing a uniform and highly controlled production process. The intra- and inter-production lot variability in the FRP material properties are inevitable under which the mechanical (and even the geometrical) properties of the FRP composites can randomly assume any value within an apparent range. Such random variability is prevalently described through the statistical parameters (such as the mean, the standard deviation and the coefficient of variation) of the FRP material properties.

The *phenomena-reliant variability* is attributed to the change in material properties under the influence of a specific physical phenomenon, such as environmental deterioration and/or mechanical degradation of FRP. Unlike the random variability, the phenomena-reliant variability shows variation of mechanical properties of FRP along a specific trend. Under the environmental and mechanical phenomena, the trend of the variability of the FRP material properties is gradual reduction along time.

Various FRP manufacturing processes involve different extents of quality controls and hence the resultant FRP exhibits different efficiency in utilising the properties of the constitutive fibres and resins. The *process-reliant variability* is attributed to these factors and reflects the relative superiority or inferiority of the FRP composites manufactured through different manufacturing processes.

2) *Behavioral Uncertainties*

For practical reasons, the strengthening design process has to rest on various design assumptions. Additionally, the analytical models devised to represent various empirically observed phenomena also carry simplifications and imprecisions. While such assumptions and simplifications provide ease in design application, they instigate the behavioral deviations compared to the real fundamental mechanics. This leads to the anticipated response by the design guidelines being different than the reality. This forms the class of uncertainties called the *behavioral uncertainties*. The important simplifying design assumptions involved in the strengthening include:

- a) Linear strain distribution along the depth of the section, both before and after loading and before and after strengthening.
- b) No relative slip between the externally-bonded FRP and the concrete substrate.
- c) Very thin adhesive layer making it possible to neglect the shear deformation within the adhesive layer.
- d) The constitutive relationship of the FRP composites is linear elastic.

- e) The externally-bonded FRP debonds at a particular strain value in FRP reinforcement.

IV. MEANS OF CONSERVATIVENESS

It is the typical approach in engineering design to prescribe a safety parameter for accounting a particular type (or group) of uncertainty. The FRP-based strengthening design also follows the same approach. Important safety parameters employed in most FRP-based strengthening design guidelines are presented in Table 1. The corresponding comparable parameters for concrete and steel (typical values) are also included in this table.

TABLE I
SAFETY PARAMETERS IN FRP-BASED STRENGTHENING DESIGN

Safety Parameter (S.P.)	Relevant Uncertainty	Typical Numerical Values					
		FRP		Conc-crete	Steel		
		A	T				
Statistical S.P.	k	Random Variability	E	0	2.00	---	---
			ϵ	3.00	2.00	---	---
			f	3.00	2.00	1.64	1.64
Phenomena-Reliant S.P.	γ_1	Phenomena-Reliant Variability	E	1.00	1.10 to 1.80	---	---
			ϵ	1.05 to 2.00	1.25 to 1.95	---	---
			f	1.05 to 2.00	1.38 to 3.51	1.50*	1.15*
Process-Reliant S.P.	γ_2	Process-Reliant Variability	E	1.00	1.05 to 1.50	---	---
			ϵ	1.00	1.05 to 1.50	---	---
			f	1.00	1.10 to 2.25	---	---
Compensatory S.P.	ψ	Behavioral Deviations	F	1.00	1.00	---	---
			S	0.85	1.00	---	---
			U	0.85	1.00	---	---
			w	0.95	1.00	---	---
Punitive S.P.	ζ	Reduction in Ductility	F	0.65 or 0.90	0.87 or 1.00	---	---
			S	1.00	1.00	---	---
			U	1.00	1.00	---	---
			w	1.00	1.00	---	---
Regulatory S.P.	ϕ	Top-up of Safety-Margin	F	0.85	1.00	---	---
			S	0.75	1.00	---	---
			U	0.75	1.00	---	---
			w	0.75	1.00	---	---

*These are not explicitly meant for phenomena-reliant uncertainties.

[†]These parameters are prescribed as partial factors of safety.

[‡]These parameters are prescribed as strength reduction factors.

A and T represent ACI440 [3] and TR55 [4] guidelines respectively.

E , ϵ and f represent modulus of elasticity, tensile strain and strength respectively.

F indicates flexural strengthening.

S, U and W represent side, U and full-wrapping configurations respectively for shear strengthening.

It is to be noted that these parameters are philosophically exclusive and independent of one another. Therefore design guidelines can exclude or include some of them without

affecting the design flow. However, such exclusion or inclusion reflects in the safety-content available in the strengthening design solutions. It is to be noted that the safety parameters dealing with constitutive uncertainties are attached through FRP material properties whereas those dealing with behavioral uncertainties are attached to the resistance contribution of the FRP reinforcement. Therefore, these are respectively called *material* and *resistance safety parameters*. There are three salient points to note here. First, the externally-bonded FRP reinforcement involves far more safety parameters than concrete and steel. Second, the material safety parameters on FRP are much more stringent for TR55 [4] compared to ACI440 [3]. Third, for most conditions, TR55 [4] does not specify the resistance safety parameters. For an arbitrary FRP property Y , these parameters can be presented through Eqs. (1)-(4) [8–10].

$$Y_d = \frac{\bar{Y}}{[S_Y]} \quad ([S_Y] \geq 1) \quad (1)$$

$$[S_Y] = \frac{\gamma_1 \gamma_2}{1 - k \left(\frac{\sigma_Y}{\bar{Y}} \right)} \quad (2)$$

$$R_{fd} = \frac{R_m}{[J]^{-1}} \quad ([J]^{-1} \geq 1) \quad (3)$$

$$[J]^{-1} = \frac{1}{(\phi \zeta \psi)} \quad (4)$$

Here, \bar{Y} and Y_d are the mean and the design values of property Y respectively, with σ_Y as its statistical standard deviation. The parameter $[S]$ and $[J]^{-1}$ respectively indicate material and resistance safety parameters presented in the condensed format. The subscript Y to the former indicates that it belongs to material property Y .

V. SENSITIVITY OF SAFETY PARAMETERS

At this point, an important distinction between the parameters $[S]$ and $[J]^{-1}$ is to be highlighted. Since the parameter $[S]$ is attached to material properties at the beginning of the design process, it propagates through entire design process. Unlike this, the parameter $[J]^{-1}$ is directly attached on the resistance at the end of the design process, and hence does not propagate through the design process. Thus, the quantitative prescription of the parameter $[S]$ can influence the governing failure modes for FRP, unlike parameter $[J]^{-1}$. It is also to be noted that out of the possible failure modes for externally-bonded FRP reinforcement, i.e. rupture and debonding, the latter is generally prescribed as a specific limiting strain value in FRP ($\varepsilon_{fd-debond}$), generally independent of FRP rupture strain ($\varepsilon_{fd-rupture}$) (especially for flexural strengthening). Thus, the FRP failure mode involving debonding remains largely uninfluenced of the prescription of parameter $[S]$. Consequently, for the design solutions governed by FRP-debonding, the prescribed safety parameters on material properties do not propagate up to the final design output (i.e. the resistance contribution of FRP reinforcement). It can also be seen that the sensitivity of the resistance safety parameters is relatively straight forward to

infer compared to that of the material safety parameters. The quantitative prescription of material safety parameters, in fact, influences the design process to a great extent. Comprehending the implications of the prescription of material safety parameters is thus of significant use in calibration strengthening design criteria. The implications of the material safety parameters from the point of views of governing failure modes, debonding and conservativeness of the design solutions are discussed below:

1) Influence on Governing Failure Modes

The governing design failure strain (ε_{fd}) for externally-bonded FRP reinforcement is presented through Eq. (5). Based on this relation, the possibility for the design solution to be governed by rupture or debonding of FRP can be portrayed through Eqs. (6) and (7).

$$\varepsilon_{fd} = \text{Min} [\varepsilon_{fd-rupture}, \varepsilon_{fd-debond}] \quad (5)$$

$$\varepsilon_{fd-rupture} \left(= \frac{\bar{\varepsilon}_f}{[S_\varepsilon]} \right) \geq \varepsilon_{fd-debond} \Rightarrow \text{Debonding Governs} \quad (6)$$

$$\varepsilon_{fd-rupture} \left(= \frac{\bar{\varepsilon}_f}{[S_\varepsilon]} \right) < \varepsilon_{fd-debond} \Rightarrow \text{Rupture Governs} \quad (7)$$

Here, the subscript ε to parameter $[S]$ indicates that it belongs to FRP rupture strain property. It can be seen that the prescription of the material safety parameters directly influences these governing criteria. The occurrence of debonding is a physical phenomenon. Hence, the prescription of debonding criteria is largely based on empirical observations and there is not much scope in the hand of the calibrator in its prescription. Unlike this, the prescription of material safety parameters (on FRP-rupture strain capacity) involves considerable subjective judgment. A quantitatively stringent prescription of material safety parameter theoretically reduces the chances of debonding to govern the design solution, while the reality might be different than this.

2) Influence of Debonding Strain Limit (Calibrator's Perspective)

From Eqs. (6) and (7) it can further be deduced that there exists a threshold value for parameter $[S_\varepsilon]$, designated as $[S_\varepsilon]_{crit}$, as shown in Eq. (8). Eqs. (9) and (10) provide the limiting conditions under which rupture or debonding of FRP governs the design solution. These expressions provide highly useful insight into the impacts of the quantitative prescription of material safety parameters on governing failure modes, especially when the issue of multiple possible failure modes of FRP is addressed through a relative condition such as the one portrayed in Eq. (5).

$$[S_\varepsilon]_{crit} = \frac{\bar{\varepsilon}_f}{\varepsilon_{fd-debond}} \quad (8)$$

$$[S_\varepsilon] \leq [S_\varepsilon]_{crit} \Rightarrow \text{Debonding Governs} \quad (9)$$

$$[S_\varepsilon] > [S_\varepsilon]_{crit} \Rightarrow \text{Rupture Governs} \quad (10)$$

Fig. 3 presents the sensitivity profiles for parameter $[S_\varepsilon]_{crit}$

for different debonding strain limits. The highlighted part in this figure indicates the zone covered by the most practical ranges of the specified values of parameter $[S_\varepsilon]$ and $\bar{\varepsilon}_f$ (i.e. [1.5 to 3.7] and [0.02 to 0.03] respectively).

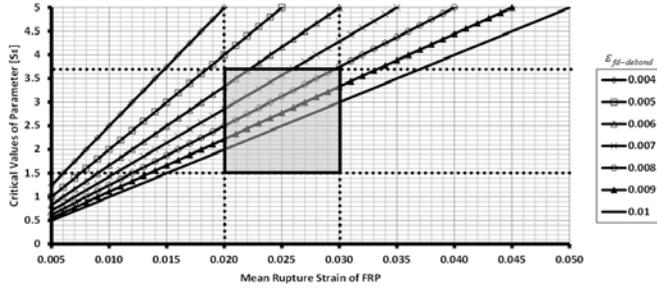


Fig. 3 Sensitivity Profiles for Parameter $[S_\varepsilon]_{crit}$

3) Influence of Debonding Strain Limit (Designer's Perspective)

While Eqs. (8)-(10) are useful for the calibration of safety parameters for the strengthening design guidelines, an expression [Eq. (11)], useful for design engineers, can also be derived on similar basis. According to Eq. (11), a threshold value on mean FRP rupture strain, designated as $\bar{\varepsilon}_{f-crit}$, can be worked out, which acts as an upper-bound on mean FRP rupture strain ($\bar{\varepsilon}_f$). For given other conditions, selection of FRP material with rupture strain capacity greater than the $\bar{\varepsilon}_{f-crit}$ results into no extra benefit, as the design solution in that case will be governed by debonding and not rupture of FRP [Eqs. (12) and (13)].

$$\bar{\varepsilon}_{f-crit} = [S_\varepsilon] \varepsilon_{fd-debond} \quad (11)$$

$$\bar{\varepsilon}_f > \bar{\varepsilon}_{f-crit} \Rightarrow \text{Debonding Governs} \quad (12)$$

$$\bar{\varepsilon}_f \leq \bar{\varepsilon}_{f-crit} \Rightarrow \text{Rupture Governs} \quad (13)$$

Fig. 4 presents the sensitivity profiles for $\bar{\varepsilon}_{f-crit}$ for various debonding strain limits. The highlighted part in this figure also presents the zone covered by most practical values of parameter $[S_\varepsilon]$ and $\bar{\varepsilon}_f$. It can be seen that these profiles serve as the benchmark for the designer in choosing the FRP material for efficient use in strengthening.

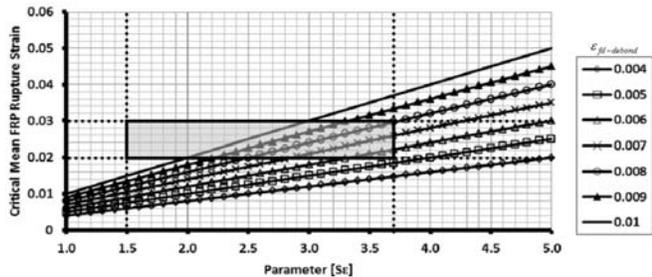


Fig. 4 Sensitivity Profiles for Parameter $\bar{\varepsilon}_{f-crit}$

4) Influence on the Resultant Conservativeness

A little consideration will show that the conservativeness available in the design solutions that are governed by FRP

debonding [Eqs. (6) and (7)] is solely dependent on the parameter $[J]^{-1}$, which comprises of the safety parameters attached on resistance. Thus, a lack of resistance safety parameter carries substantial negative implications in terms of the conservativeness available in the resultant design solutions, and in turn, in terms of their reliability. It is again to be highlighted that the absence of resistance safety parameters for most cases in TR55 will lead to reduced conservativeness, in spite of the prescription of relatively stringent material safety parameters.

VI. INFERENCES

Following salient points can be inferred from Figs. 3 and 4:

- For a given debonding strain limit, with increasing rupture strain capacity of FRP material, the corresponding $[S_\varepsilon]_{crit}$ value increases linearly. This implies that a quantitatively higher prescription of material safety parameters is more suitable for FRP materials with high rupture strain capacity.
- For a given FRP rupture strain capacity, an increased debonding strain limit (through mechanical anchors or otherwise) reduces the corresponding values of $[S_\varepsilon]_{crit}$. This can lead to more rational and efficient use of FRP composites.
- Prescription of resistance safety parameters is highly crucial in regulating required conservativeness in design solutions for the strengthening through externally-bonded FRP reinforcements, which involves multiple failure modes possible for FRP reinforcement.

It can be appreciated that the observations and the expressions presented in this paper are of great use in calibrating design criteria for FRP-based structural strengthening systems and in their design.

VII. SUMMARY AND CONCLUSIONS

A conceptual overview of the conservativeness hypothesis for FRP-based structural strengthening is presented. The relation between conservativeness in the resistance contribution of FRP reinforcement and the safety-content of a design solution is portrayed. Various uncertainties and safety parameters accounting for these uncertainties are discussed. Mathematical expressions depicting the governing failure modes for FRP are suggested. These expressions are presented in the forms useful for the calibrators and the designers. The implications of quantitative prescriptions of material safety parameters on the strengthening design process are discussed.

VIII. ACKNOWLEDGEMENTS

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