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# Design by testing procedure for intermediate debonding in EBR FRP strengthened RC beams

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ABSTRACT

Externally bonded (EB) Fiber-Reinforced-Polymer (FRP) sheets and laminates are widely employed for enhancing the bending capacity of reinforced concrete (RC) beams. However, the adhesion between FRP and concrete substrate is an issue of concern and generally controls the ultimate capacity of RC beams. Particularly, intermediate debonding phenomenon which begins from an intermediate point throughout the FRP-concrete interface is one of the most common and peculiar failure modes observed in RC beams externally strengthened in bending by bonded FRP.

The present paper applies a well-established procedure for calibrating a design formula for determining the maximum axial strain developed in FRP at the onset of intermediate debonding failure. The procedure is based on the well-known design-by-testing approach based on the availability of a wide collection of experimental results.

General behavioral observations are firstly derived by analyzing a large number of experimental results available in the scientific literature and collected by the authors. Such results are finally used for calibrating a design formula which looks after the key mechanical parameters controlling the bond behavior. The model uncertainties are handled through a consistent statistical procedure leading to a sound definition of the characteristic value of the relevant design quantities.



## 1. Introduction

Externally bonded FRP fabrics or laminates are more and more common as one of the possible solutions for enhancing flexural capacity of RC members [1]. Although alternative systems are possibly available to connect the FRP strip to concrete members [2,3], external bonding is still the most common and effective technique. However, the possible premature failure due to debonding between adhesive layer and concrete substrate often control such a strengthening technique. Based on experimental observations, it can occur either at the beam end (end debonding) or in the cracked zone (intermediate debonding) [4].

According to well-established mechanical models, end-debonding is basically due to the high interface shear stresses developing in the neighborhood of the FRP cut-off section as a result of the abrupt change in the transverse section of the strengthened beam [5,6].

By contrast, a higher level of uncertainty still overshadows the mechanical understanding of intermediate debonding due to the complex interaction of several phenomena, such as cracking in concrete, steel yielding in longitudinal rebars, and interface adhesion properties [7]. As a result of this partial understanding, different alternative analytical approaches were proposed within the scientific literature and adopted by the most common codes of standards for performing the required safety checks [5,6,8,9]. A possible classification of those approaches based on the nature of the procedures utilized for checking the strengthened beam against intermediate debonding is proposed in [10]. Since such procedures work in rather diverse ways, consider various sets of relevant parameters and adopt different relationships for defining interface properties, they generally lead to rather diverse predictions of the ultimate load resulting in intermediate debonding.

Moreover, such procedures actually neglect or disregard the role played by several mechanical parameters in controlling the structural response of FRP-strengthened RC beams, by adopting simplified empirical formulae usually calibrated on the available experimental observations.

As a matter of principle, two different methodological approaches can be followed for defining reasonably simplified design formulae based on experimental results:

– direct calibration of empirical expressions against experimental results by means of well-established mathematical procedures, such as the least-square minimization of the overall difference between the experimental observations and the corresponding analytical values;

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– validation of refined numerical models (i.e. based on finite element simulation) by means of a limited number of experimental results and extrapolation of such results by means of the above mentioned numerical procedures.

The two above mentioned "paths" are schematically represented in Fig. 1, where three conceptual blocks are alternatively connected by either a continuous line or a dashed one.

Starting from a model previously developed by the authors to analyze steel-concrete beams and frames in partial interaction [11], a numerical procedure was formulated and validated in [12] and used for pointing out the role of some mechanical parameters (currently neglected or disregarded in most well-established simplified formulae) which affect the mechanical response of FRP strengthened RC beams. Such a numerical model was calibrated on a wide collection of experimental results. Since it is based on consistent mechanical assumptions, it was utilized for extrapolating the results of such experiments beyond their limited parametric range. In particular, it pointed out the key importance of yielding in steel rebars as a driving phenomenon for leading to intermediate debonding failure. Moreover, it shed new light on the correlation between the ultimate moment at debonding, $M_{db}$, and the corresponding moment at yielding, $M_{y,sf}$, evaluated for the transverse section of the strengthened beam [13].

The role of further parameters (i.e. load condition, yielding strain of steel rebars, amount of reinforcement) was also pointed out, though it is not easy to be assessed through the available experimental results because of the limited range of variation of such parameters actually explored in the experimental tests. Thus, the most common approaches derive from empirical approaches and generally recognize the key role of the interface fracture energy $G_F$, whose experimental determination is not straightforward [14].

Since the premature failure due to FRP debonding generally leads to a reduction of ductility in RC beams strengthened with EB-FRP sheets/laminates a more refined estimation of the debonding strain allows a more reliable assessment of the beams capacity, in terms of strength as well as in terms of ductility (e.g. ultimate curvature). Furthermore, the quantitative information about the uncertainty which affects debonding prevision of both FRP sheets and laminates can be considered for calibrating further partial safety factors for cases in which ductility requirement is fundamental.

With this in mind, a simplified design formula based on a well-established statistical approach, originally stated in EC0 [15], is proposed in the paper. The application of this approach implements the methodology proposed in [16] and used in [17] for the FRP end-debonding load, on a wide collection of more than two hundred experimental results available in the scientific literature [18–24] related to intermediate crack debonding.

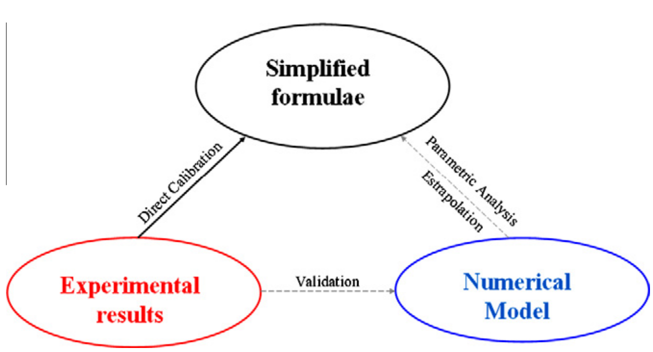


**Fig. 1.** Methodological framework for deriving design formula from experimental data.

## 2. Theoretical models and code provisions

Several theoretical models are presented in the scientific literature to check RC beams externally strengthened with FRP against the possible premature failure due to intermediate debonding. Some of these models were adopted in the existing codes of standards. Since a wide variety of proposals are actually available, a general classification of the various possible approaches is firstly proposed [10]:

– models which define a maximum value for the axial strain $\varepsilon_{fd}$ developing in the FRP strip at the onset of the intermediate debonding failure;
– models defining a maximum gradient of axial stresses $\sigma_f$ in the FRP strip (i.e., the maximum stress variation $\Delta\sigma_f$) between two adjacent bending-induced cracks);
– models defining a maximum shear stress $\tau_{db}$ resulting in the beam to fail in intermediate debonding.

It is worth noting that last two approaches are rather close to each other. A clear relationship between axial stress gradient $\Delta\sigma_f$ and interface shear stress $\tau_{db}$ can easily be recognized once strip thickness and distance between two cracks under consideration for determining the above mentioned stress gradient.

Beyond the slight differences in the numerical details, the three alternative approaches can easily be recognized in design formulae currently adopted by current codes of standards. A short review of such proposals is outlined in the following subsections.

### 2.1. ACI 440.R2 (2008)

The ACI 440 [6] provisions are clearly inspired at the first class of models defining a maximum value for the axial strain $\varepsilon_{fd}$ which can be developed in the FRP strip. In particular, such a maximum strain should be limited to the strain level, $\varepsilon_{fd}$, at which debonding is supposed to occur (ACI 440.R2, 2008 [6] – Eq. (10-2)):

$$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c'}{nE_f t_f}} \leq 0.9\varepsilon_{fu}. \tag{1}$$

Eq. (1) is slightly different from a similar equation proposed in [26] and outlined in the following. It was based on the best fit of a group of experimental results obtained from beams failed in intermediate debonding. Thus, proposed equation refers to average values of axial strains develop in FRP at debonding. Uncertainties deriving by adopting the analytical expression in Eq. (1) are covered by considering both the usual strength reduction factor $\phi$ considered by ACI 318-05 [27] for structural concrete and an additional strength reduction factor $\psi_f$ for FRP strips.

### 2.2. JSCE recommendations (2001)

The Japanese Code of Standards (2001) [8] introduces an explicit methodology for checking the FRP strengthened beams against the premature failure due to the possible loss of bonding. Both end and intermediate debonding are addressed in the proposed procedure. In particular, the approach adopted for intermediate debonding can be categorized within the second one of the classes listed at the beginning of this section.

Pull-out tests and theoretical studies pointed out that the ultimate strength of a FRP-to-concrete adhesive joint depends on the interface fracture energy $G_f$ (mainly in mode II with fracture in shear) of concrete, on the Young modulus $E_f$ and thickness $t_f$ of the FRP reinforcement. Based on well-established experimental and theoretical findings, the following check can