GENERIC DEBONDING MECHANISMS IN FRP PLATED BEAMS AND SLABS

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ABSTRACT

National codes and standards such as those for reinforced concrete, steel and composite steel and concrete structures are invariably based on generic and fundamental behaviours and principles that allow them to be used with confidence and over a wide range of applications. Hence, before the technique of retrofitting by FRP plating can be fully accepted and applied in practice, it will be necessary to identify generic behaviours which will allow generic design rules to be developed and which is the subject of this paper.

KEYWORDS

FRP, RC beams, debonding, debonding mechanisms

INTRODUCTION

Reinforced concrete (RC) beams and slabs are subject to fundamental flexural and shear deformations that are peculiar to reinforced concrete and which are generally well understood by RC designers and researchers. It is these fundamental reinforced concrete deformations that induce fundamental internal forces which cause FRP plates attached to the beam to debond. Hence, the first step in understanding and identifying the generic and fundamental debonding mechanisms is to understand the fundamental behaviour of RC beams which is first explained. From the generic behaviour of RC beams, the fundamental stress resultants within the beam are deduced which are then used to explain the generic mechanisms that cause debonding within RC beams. This is then followed by a description of the generic plate/concrete interface behaviours which are used to further explain the generic mathematical models for the various unique and distinct debonding mechanisms which allows the development of generic design rules for both the strength and ductility of plated RC beams.

The emphasis in this paper is on identifying generic and fundamental principles as these are the prerequisites for developing a generic standard that applies to all forms of plating which can be applied to all forms of RC structures. It is only when this generic approach is achieved will the technique of retrofitting by plating reach the same status as established design codes such as for reinforced concrete, steel and composite steel and concrete structures.

GENERIC FLEXURAL DEFORMATION MECHANISMS

A standard cross-sectional flexural analysis of an RC beam is shown in Fig.1 (Oehler and Seracino 2004). For unplated RC beams with ductile reinforcing bars, failure is always caused by concrete crushing at a strain \( \varepsilon_c \). In contrast, a plated beam can also fail by plate debonding at a strain \( \varepsilon_{db} \) or plate fracture at a strain \( \varepsilon_{fr} \). Hence, in plated beams three strain failure mechanisms have to be considered instead of one strain failure mechanism in unplated beams as shown in Fig.1(b). The strain profile is then pivoted about the failure strain as shown in Fig.1(c) where in this example plate debonding is assumed to cause failure. The curvature is varied until from the stress distribution in Fig.1(d), the force distribution in Fig.1(e) is in longitudinal equilibrium. It is worth noting, that if plate debonding or fracture precedes concrete crushing then allowance must be made for the concrete to remain at least partly elastic as shown in Fig.1(d). It is also worth noting that the stresses in the plate induce both an axial force \( P_{plate} \) and a moment \( M_{plate} \) as shown in Fig.1(f). For tension face plates as in Fig.1(a), the plate moment \( M_{plate} \) may be quite small.
A clearer indication of the development of the plate moment is shown in Fig.2 for a side plated beam which also represents tension face near surface mounted (NSM) plates. The non-uniform stress distribution in the plate in Fig.2(c) induces a moment about the plate centroid and an axial force through the plate centroid as in Fig.2(e).

The plate moment $M_{\text{plate}}$ in Fig.2 is resisted by transverse forces $V_{\text{plate}}$ as shown in Fig.3. Therefore the bond between the plate and the RC beam must be designed to resist both longitudinal forces $P_{\text{plate}}$ as well as transverse forces $V_{\text{plate}}$ induced by curvature. These forces have been long recognised in the bolting of plates as shown in Fig.3. Hence, whether the plate is adhesively bonded or bolted these generic and fundamental stress resultants occur and have to be designed for.

**GENERIC SHEAR DEFORMATION MECHANISMS**

The behaviour of RC beams under shear is much more complex than that under flexure. What is known is that the forces in the reinforcement are minimal and can be ignored until a critical diagonal crack (CDC) forms. An example of a CDC in a beam without stirrups is shown in Fig.4, and it is this failure of a beam without stirrups which is directly associated with the concrete component of the shear capacity of the beam $V_c$. The presence of stirrups tends to hide the importance of the initial CDC as shown in Fig.5 where a series of diagonal cracks can be seen. However, it should be remembered that the formation of the first or initial CDC in a beam with stirrups occurs at the same shear load $V_c$ as that of a beam without stirrups as the formation of the first CDC often causes debonding in beams with and without stirrups.

The rigid body shear deformation across the CDC then induces forces in the reinforcement which could be in the form of longitudinal reinforcing bars, longitudinal plates, transverse stirrups or transverse plates. Critical diagonal cracks should not be confused with shear/flexural cracks where rigid body displacement does not occur.
Critical diagonal cracks are associated with rigid body displacements across the crack, are directly associated with the concrete component of the shear capacity of the beam \( V_c \), and are required to stretch the internal stirrups to induce their contribution \( V_s \).

Existing procedures for quantifying the shear capacity of RC beams simplify this extremely complex problem by assuming that the longitudinal reinforcing bars contribute indirectly to the concrete component of the shear capacity \( V_c \) and that the transverse bars or stirrups contribute directly to the shear capacity \( V_s \). Following this simplistic but convenient approach, longitudinal FRP plates can be assumed to indirectly increase \( V_c \) as shown in Fig. 6 by holding the two faces of the CDC together and, thereby, through the axial forces in the longitudinal plates increase the shear resisted by aggregate interlock \( \Delta V_c \).

Transverse plates can be considered to act in the same way as the internal steel stirrups \( (V_s) \), that is these external stirrups directly resist the vertical shear through their axial forces \( V_{tp} = \sum P_{\text{plate}} \) as shown in Fig. 7.

**GENERIC PLATE INTERFACE DEBONDING MATERIAL FAILURE**

Fundamental to the whole concept of plate debonding are the bond characteristics at the interface between the plate and the concrete. The interface is subjected to both interface shear stresses and stresses normal to the interface due to the fundamental deformations of RC beams that has been described previously. It will be assumed in this section that the adhesive is strong enough to ensure failure within the concrete. This is usually the case as the adhesive and its bond are normally several times stronger than the tensile strength of the concrete.

**IC debonding interface material resistance**

When a crack intercepts a plate, infinite strains need to be induced in the plate to accommodate the crack which of course cannot occur. Hence the stress concentrations induced by the crack intercepting the plate cause cracking in the concrete adjacent to the interface. Shear can still be transferred across this crack through aggregate interlock which requires localised forces or stresses normal to the interface. This IC debonding material behaviour is often determined directly from pull-tests as shown in Fig. 8 where the front of the block is equivalent to a crack face and where the material shear \( (\tau) \) slip \( (\delta) \) characteristics are either determined directly or indirectly. The interface IC debonding \( \tau/\delta \) material characteristics are of profound importance to the behaviour.
of plated structures and there has been recently much very good research in quantifying this material characteristic which is often idealised as bi-linear as shown in Fig.9.

Concrete interface resistance

The plate/concrete interface can also fail in the absence of the aggregate interlock that is required when debonding propagates from the stress concentrations induced by cracks intercepting plates. Take for example the stresses that are induced at the plate end due to curvature in the beam and where, because the plate is simply trying to stay straight, debonding propagates from the plate-end inwards. In this case, there are large normal stresses to the plate which can be assumed to be directly resisted by the tensile strength of the concrete. There can also be interface shear stresses which are at a maximum near the plate end. However it is felt that the mechanism that occurs in developing the IC debonding interface material resistance, in particular that required for aggregate interlock, does not occur when debonding initiates from the plate end. Hence the $\tau/\delta$ interface characteristics are not applicable to the interface shear stresses so that the interface strength may be directly related to the tensile strength of the concrete.

Away from stress concentrations at the intercept of a crack or at the plate-end due to the discontinuity of the plate, the interface shear stress $\tau$ is given by the well known elementary equations of $VA_y/lb$ or $VQ/lb$. This form of debonding rarely controls design so that it is suggested the shear stresses can be directly related to the tensile strength of the concrete.

**GENERIC DEBONDING MECHANISMS**

**Externally bonded tension face plate guidelines**

Most national guidelines deal with tension face plated beams and it is felt that within these guidelines there is already a general consensus as to the major debonding mechanisms, even though each guideline may use its own terminology as shown in the table in Fig.10. All the guidelines acknowledge IC (intermediate crack) debonding due to flexural cracks in the beam and do distinguish between the behaviours of IC debonding at the anchorage zone shown in column 1 and IC debonding due to a succession of flexural and flexural/shear cracks as in columns 2 and 3; this form of debonding is controlled in the guidelines through limitations to the plate strains.

<table>
<thead>
<tr>
<th>Guidelines</th>
<th>Debonding mechanisms</th>
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<tbody>
<tr>
<td>AUST: IC debonding</td>
<td>EUR mode 1: peeling off in uncracked anchorage</td>
</tr>
<tr>
<td>EUR mode 2: peeling off at flexural crack</td>
<td>BRT: debonding failure</td>
</tr>
<tr>
<td>BRT: IC induced debonding</td>
<td>H.K.: IC induced</td>
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<tr>
<td>USA: referenced</td>
<td>USA: refer.</td>
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<tr>
<td>AUST: CDC debonding</td>
<td>EUR mode 3: peeling off at flexural crack</td>
</tr>
<tr>
<td>BRT: IC induced debonding</td>
<td>H.K.: plate end</td>
</tr>
<tr>
<td>USA: refer.</td>
<td>USD: PE debonding</td>
</tr>
<tr>
<td>EUR: (mode 6): concrete rip-off</td>
<td>BRT: plate end</td>
</tr>
<tr>
<td>USA: not recognised</td>
<td>USA: refer.</td>
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All the guidelines acknowledge CDC (critical diagonal crack) debonding due to rigid body shear deformations as in column 4 in Fig.10 and often quantify this form of debonding by adjusting the concrete component of the shear capacity $V_C$. Most guidelines acknowledge PE (plate end) debonding due to curvature as in column 5 but may not give design rules. This is understandable for the European approach in which it is required to terminate the plate in an uncracked region which is invariably near to the point of contraflexure where the curvature is low, and in which only very thin FRP externally bonded (EB) tension face plates are used which further reduces the interface normal stresses; under these circumstances PE debonding is unlikely to occur. Few guidelines directly acknowledge $VA_y/lb$ debonding between stress concentrations shown in the block marked 6.
Axial deformations

Research has shown that the axial intermediate crack (AIC) debonding resistance in pull-tests as in Fig.8 (where the plate is only subjected to axial deformations and subjected to the equivalence of one crack and debonding is characterised by the \( \tau/\delta \) material properties in Fig.9) is a lower bound or equal to the flexural IC intermediate crack (FIC) debonding resistance in beams. Hence the AIC debonding resistance in pull-tests is a fundamental property.

The governing mathematical equations based on the \( \tau/\delta \) characteristics in Fig.9 have been developed at Hong Kong Polytechnic University for predicting the partial-interaction AIC debonding resistance in pull-tests. Partial-interaction theory based on the rising branch in Fig.9 has been well established over fifty years in the analysis of composite steel and concrete structures (Oehlers and Bradford 1995). However, the research at Polytechnic University developed partial-interaction solutions to the falling branch for the first time and is, hence, outstanding ground breaking research. This research was then used at Adelaide University in Australia to predict the AIC debonding resistance in fully anchored plates based on the falling branch only as this allowed a closed solution. In this research, the failure plane was also separated from the geometry of the plate to give the following fundamental AIC debonding resistance which can be applied to both externally bonded (EB) plates and near surface mounted (NSM) plates as in Fig.11.

\[
P_{\text{AIC}} = \sqrt{\tau / \delta} \sqrt{L_{\text{per}} (EA)_p}
\]

where \( \tau/\delta \) is twice the area under the idealised \( \tau/\delta \) characteristics in Fig.9, \( L_{\text{per}} \) is the length of the failure plane in Fig. 11 and \( (EA)_p \) is the axial rigidity of the plate which can also include the axial stiffness of the adhesive bonding the plate. This is a convenient form as it no longer depends directly on the plate or glue thicknesses which may be difficult to measure particularly for the wet lay-up procedure and, furthermore, the same equation applies to both EB and NSM plates and is, therefore, generic.

The research at Adelaide then experimentally quantified the \( \tau/\delta \) parameter in Eq.1 to give the following design equation

\[
P_{\text{AIC}} = 0.78 \left( \frac{d_f}{b_f} \right) f_c \sqrt{L_{\text{per}} (EA)_p}
\]

where \( d_f \) and \( b_f \) are the depth and width of the failure plane as in Fig.11 and \( f_c \) the cylinder compressive strength. The parameter \( d_f/b_f \) can be considered to be a confinement factor that allows for the increase in the IC material characteristics of strength (\( \tau \)) and ductility (\( \delta \)) due to confinement; the better the confinement, the better the aggregate interlock. The axial IC debonding resistance of Eq.2 can predict the IC debonding resistance of wet lay-up plates of equivalent thicknesses of 0.12 mm to NSM plates of depth 26 mm and may, therefore, be considered as generic.

Flexure deformations – FIC debonding

An example of flexural intermediate crack debonding (FIC) of an externally bonded (EB) plate due to flexural deformations in a beam is shown in Fig.12. A further example of FIC debonding in a NSM plated beam is shown in Fig.13. Both examples of debonding, in Figs.12 and 13 are controlled by the same interface \( \tau/\delta \) characteristics in Fig.9. Figure 13 shows the classical herringbone formation of cracks associated with shear failure of concrete. The flexural cracks (vertical in the figure) first form and then between these cracks the plate gradually debonds as can be seen by the herringbone cracks (inclined cracks) on either side of the NSM plates (horizontal). Importantly, debonding (herringbone cracks) starts from the flexural cracks and from where the
strains are at their maximum and spread outwards. Towards the centre of the beam and between flexural cracks, these herringbone cracks are inclined in opposite directions clearly showing the opposing directions of the interface shear forces. In some regions they are in both directions (crossing each other) showing that the shear forces start in opposite directions and then change to the same direction due to slip between the concrete teeth. Towards the ends of the herringbone crack formation, the herringbone cracks are in one direction as in a pull test.

Each concrete tooth (block of concrete between flexural cracks) in Fig.13 can be considered to act as a shear connector (as in composite steel and concrete beams) imposing some force on the plate. The ends of the herringbone formation are anchorages equivalent to pull tests. This mechanism, of concrete-teeth and end anchorages, explains why the FIC debonding resistance in beams can be greater than the AIC debonding resistance in pull-tests. However, the problem is complex. If the beam were under high vertical shear forces, then only one flexural crack would occur, hence, the FIC resistance would tend to the AIC resistance. If the beam were subjected to a constant moment region in which the vertical shear is zero, then within the constant moment the concrete teeth would have a net zero shear force (as the force in the reinforcing bars on either side of the concrete tooth are the same) so the strength may also tend to the AIC debonding resistance depending on the conditions beyond the constant moment region. In between these two extremities, the FIC resistance may be greater than the AIC resistance. There is much research on quantifying this increase but it is important to realise that the AIC resistance is a lower bound or equal to the FIC debonding resistance in a beam.

**Flexure deformations – PE debonding**

An example of PE debonding of an EB plate is shown in Fig.14. In this example, the plated section is in a constant moment region so that it is only the curvature that is inducing debonding as the plate tries to stay straight inducing large interface normal tensile stresses at its ends. Importantly in this form of debonding, the cracks start at the plate-end and work inwards and for tension face plated beams they propagate along the level of the tension reinforcement. Exactly the same mechanism as in Fig.14 occurs in side plates as in Fig.15 where debonding starts at the plate-ends and works inwards, but in this case the interface stress that causes debonding is shear.

PE debonding also occurs in compression face plates as in Fig.16, but in this case the signs of the interface normal stresses reverse in direction making the resistance larger. Plate end debonding also occurs in NSM plates on the tension face as in Fig.17. In the latter three cases, Figs. 15-17, PE debonding has not caused concrete cover separation as in the tension face plate in Fig.14.
As there is a generic mechanism, as shown in Figs.14-17, that describes PE debonding, it is possible to determine generic design rules such as the following

\[
(M_{PE})_{NSM\cdot dp} = \frac{1.62(EI)_{cr\cdot pl} f_{cb}}{E_p (0.185t_{NSM\cdot dp} + 0.0185f_{bNSM\cdot dp})}
\]

which depends on the flexural rigidity of the section \( EI \), plate stiffness \( E_p \), plate thickness \( t_{bp} \) and position of the plate \( d_{cbp} \). Plate end debonding can often cause debonding but can be easily prevented by terminating the plate in a region of low curvature.

**Flexure deformations – VAy/Ib debonding**

Tests have shown that bonding due to the elementary interface shear between stress concentrations VAy/Ib seldom controls debonding but it is felt that it should be included in design as it may control debonding for prestressed beams where flexural cracks are suppressed and for serviceability where thick plates may be used to control deflections when there are few flexural cracks.

**Vertical shear deformations – CDC debonding**

An example of critical diagonal crack (CDC) debonding due to the shear deformations across a CDC in a tension face plated beam with stirrups is shown in Fig.18. Debonding is induced by the CDCs starting near the support and working inwards. It can be seen that the debonding cracks propagate outwards, as shown by the arrows, but progress inwards, as shown by the sequence numbers, and for tension face plated beams the debonding crack follows the weak zone along the level of the tension reinforcement.

CDC debonding can also be seen in the side plated beam without stirrups in Fig.19 where because of the absence of stirrups only one CDC forms. For EB plates, CDC debonding occurs before the stirrups can be stretched. CDC debonding can also occur in NSM tension face plated beams as in Fig.20 and in EB compression face plated beams in Fig.21. In the latter three cases, Figs.19-21, there is no concrete cover separation as in the tension face plate in Fig.18.

A further example of CDC debonding can be seen in Fig.22 where there are three horizontal NSM plates that cross a vertical critical diagonal crack. The rigid body shear deformation across the CDC causes the crack faces to separate through aggregate interlock inducing axial forces in the plates that induce the herringbone formation of cracks. As we are now dealing with a single crack intercepting each plate, the axial resistances of the NSM plates is their AIS debonding resistance as can be determined from pull-tests. This photograph clearly shows the dependence of the CDC resistance on the AIS debonding resistance.

The difference between FIC (flexural intermediate crack) and CDC (critical diagonal crack) debonding is that in the former the crack is widened by flexure and in the latter by aggregate interlock through shear deformations. The AIS force across the crack increases the concrete component of the shear capacity \( \Delta V_c \). There are complex generic methods for determining the CDC debonding resistance that predict the position of the CDC crack and,
hence, the extent of plating required. Alternatively generic simple approaches such as in Eq.4 can be used that require the whole shear span to be plated

\[ \Delta V_c = 0.15 \sum \left( p_{\text{plated}} \right) \]  

(4)

Unlike EB plates where debonding always occurs on the formation of the CDC crack and before the stirrups are stretched, it is worth noting in Fig.22 that the shear deformation has not actually caused the NSM plate to debond even though they increase the shear capacity \( \Delta V_c \). This is in contrast to the NSM plates on the tension face in Fig.20 where debonding has occurred because it is being deformed about the plates major axis compared with the deformations in Fig.22 that occur about the plates minor axis. It would appear that that placing NSM plates on the sides of beams subjected to large shear forces as in Fig.23 would be an appropriate design solution.

Vertical shear deformations - SIC debonding

Transverse plates act as external stirrups to increase the vertical shear capacity directly as in Fig.24 (Teng et al 2002). This is an example of a plate crossing a single crack so that the debonding resistance of an individual plate is its AIC debonding resistance as shown in Fig.7.

The debonding resistance of each plate in Fig.24 depends on their minimum anchorage lengths on either side of the CDC which can be seen to vary, and also on the \( \tau/\delta \) characteristics in Fig.9. Hence as the CDC widens each plate achieves its maximum capacity at differing crack spacings so that the plates with short anchorage lengths will achieve their maximum capacities and debond before plates with larger anchorages achieve theirs. Hence if \( V_{tp} \) is the sum of the maximum possible plate axial forces, that is each plate can achieve its maximum strength, then debonding will occur before the shear resisted by the plates achieves \( V_{tp} \) so that the reduction factor \( k_{tp} \) in Eq.5 is less than unity.

\[ V_{\text{cap}} = V_c + \Delta V_c + k_t V_t + k_{tp} V_{tp} \]  

(5)

Furthermore, the plates may debond before the stirrups reach their maximum yield capacity \( V_t \), so that the reduction factor \( k_t \) may also be less than unity. Hence the interaction between plates \( (k_{tp}) \) and that between the plates and the stirrups \( (k_t) \) has to be considered. Partial-interaction theory based on the falling branch of the \( \tau/\delta \) characteristics in Fig.9 have been developed to simulate this behaviour.

The increase in the shear capacity due to inclined plates as in Fig.25 can now be accommodated by allowing the horizontal component of the AIC debonding resistance to increase the concrete component \( \Delta V_c \) in Eq.5 and the vertical component to act as stirrups contributing \( k_{tp} V_{tp} \), although allowance must be made for any reduction in the stirrup contribution \( k_t V_t \).
Concrete cover separation

Concrete cover separation is a frequently used term to describe debonding failure. It is felt that even though this term is correct in describing a visually seen form of debonding, it can lead to confusion. This is because *concrete cover separation* occurs in PE debonding of tension face plates as can be seen in Fig.14 which was tested in a region of zero shear. However, *concrete cover separation* also occurs in the CDC debonding of tension face plates as in Fig.18 which occurs in regions of high shear. Hence, *concrete cover separation* occurs in two distinct forms of debonding of tension face plated beams that are induced by two distinct deformations that of either curvature or that of shear. Furthermore, *concrete cover separation* only applies to tension face plates and does not describe the same form of debonding in side or compression face plates. For example, the mechanism that causes PE debonding in Fig.14 also occurs in side plates in Fig.15, compression face plates in Fig.16 and NSM plates in Fig.17 none of which show concrete cover separation. The same can be said for CDC debonding in Fig.18 for tension face plates, which also applies to side plates in Fig.19 and to compression face plates in Fig.21 in which there is no concrete cover separation.

**SUMMARY - GENERIC DESIGN RULES FOR STRENGTH**

The identification and eventual quantification of the generic debonding mechanisms will allow engineers to use all forms of plating as illustrated in Fig.26 and hence give them the freedom to develop their own retrofitting techniques.

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**Figure 25** Shear increase due to inclined plates

**Figure 26** Range of applications of generic approaches
The understanding of the fundamental behaviour of IC debonding has allowed the development of at least two design approaches both of which are correct. In the hinge approach in Fig.27, the plate strain is limited to that from a pull test which restricts the debonding crack propagation to a small hinge region. Hence, the plates can be terminated short of the point of contraflexure and the design plate strains determined directly from pull tests.

In contrast to the hinge approach in Fig.27, the anchorage approach in Fig.28 allows larger strains than those from pull-tests as it depends on the partial-interaction between the concrete teeth; this approach requires the whole shear span to be plated. Hence the hinge approach requires thicker but shorter plates in which the debonding strains can be determined directly from pull-tests. In contrast, the anchorage approach requires thinner but longer plates where the plate strain depends on partial-interaction within the beam. The anchorage approach will also allow greater ductility due to the increased strains.

The first step in developing a generic code on par with generic established codes such as those for reinforced concrete is in identifying the generic failure mechanisms that include the generic debonding mechanisms as well as the generic interface material failure mechanisms and much good research is being done. The problem is extremely complex. We have all the deformation problems associated with reinforced concrete structures, all the partial-interaction problems associated with composite steel and concrete structures, plus the additional complexity of plate debonding. We are in effect dealing with a brand new form of structure which is more complex than any existing form of structure. I believe because of the very rapid advances over the last two years through some excellent research in understanding the failure mechanisms and in developing the structural mechanics of these failure mechanisms, we are very close to a solution.

REFERENCES

