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MECHANISMS IN COMPOSITE STRUCTURES

by

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ABSTRACT

This thesis is on understanding fundamental mechanisms that control the behaviour of composite structures. In particular: the mechanisms that control *partial shear connection*, that is the transfer of interface shear forces across two elements which is often associated with stress concentrations; and the mechanisms that control the slip across two elements which is often referred to as *partial interaction* and is associated with the stiffness of the shear connection.

Research can be categorised as *numerical modelling* such as in the use of finite elements, *experimental modelling* where tests are done in the laboratory and *mathematical modelling* where an equation or approach is developed to represent the behaviour. There is a fourth category which will be referred to as the *concept* or idea which is the essence of research as it is the idea that explains what is happening, that is the fundamental mechanism. It is felt that *numerical modelling* and *experimental modelling* are tools that may help in identifying the *concept* but do not by themselves derive the *concept* directly. Having determined the *concept, mathematical models* can then be used to develop equations or procedures that simulate the *concept*. The primary concern of this thesis is the identification of the *concept* and it is the author's personal *hunt for the illusive concept*.

Statement of Originality

This thesis does not contain material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, the thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

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ACKNOWLEDGEMENTS

Research has to start somewhere and of profound influence has been the inaugural work on Partial Interaction by Newmark, Siess and Viest[1] published in 1952 and that on Partial Shear Connection by Yam and Chapman[2] published in 1968. I acknowledge their research with thanks and have been fortunate to have met both Professors Viest and Chapman.

During my wonderings through the tangled web of research, I have been very lucky in meeting outstanding people who have had a great influence on my research and who I now consider as friends. At the forefront, I would like to thank my Ph.D supervisor Professor Roger Paul Johnson for allowing me the opportunity to do partial interaction composite research, instilling in me the thrill of research and for his lifelong guidance. To do research under such an eminent person was luck enough, to then find that composite partial interaction theory could be applied to such diverse fields as the mechanics of fatigue design and assessment, the mechanics of intermediate crack debonding of plated structures and even to understanding and modelling hinges in reinforced concrete structures was an additional bonus.

It is incredible that in the research community it is often difficult to get original research accepted. Researchers often tend not to like change, supporting shallow advances along well established longitudinal paths and rejecting any radical thinking along transverse paths. Hence on many occasions, I have found my research initially rejected through personal diatribes during which time support from my peers has often been of great moral value. I would like to thank Professor Mark Bradford for his support and friendship during these times, not withstanding the enjoyment of doing research and writing books with him. Similar thanks to Professor Brian Uy and Professor Jin-Guang Teng.

I have had a few awful research students but these are more than balanced by the enjoyment and privilege of working with some outstanding students who have greatly influenced the course of my research and allowed substantial advances. In particular: Dr. M.S. Mohamed Ali Sahib for his work on critical crack debonding, his ability to recognise transverse solutions and his humour; Dr. Ninh T Nguyen for his work on plate end debonding and his ability to find mathematical solutions even during heated discussions; Dr. Yufei Wu for his obstinate pursuance resulting in some beautiful partial interaction mathematical solutions; and (the future Dr.) Irene Liu for her outstanding work on partial interaction hinges, her conceptual imagination and for always coming in late.

And finally, a simple thanks to my wife Bernie without whom none of this would have been possible.

Ref.1: Newmark, N.M., Siess, C.P. and Viest, I.M. (1952) "Studies of slab and beam highway bridges, Part III – Small scale tests of shear connectors and composite T-beams, Bulletin 396, University of Illinois, Urban, Illinois.

Ref.2: Yam, L.C.P and Chapman, J.C. (1968) "The inelastic behaviour of simple supported composite beams of steel and concrete". Proceedings of the Institution of Civil Engineers, Vol.41, Dec. , pp 651-683.

TABLE OF CONTENTS

PUBLICATION LISTS

The following publications of three books, and seventy-two journal papers and two conference papers in the following list of seventy-five papers, form the body of work I wish to be considered for the degree of Doctor of Engineering. None of these publications contains material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution.

Please note that in the following list of seventy-five papers and clearly marked with an asterisk, I have included an additional three papers from my PhD thesis so that these can be referred to in my commentary. However, these three publications are not meant to be part of the body of work for consideration for the degree of Doctor of Engineering.

International Books

A) Oehlers, D. J. and Bradford, M. A. (1995) "Composite Steel and Concrete Structural Members: Fundamental Behaviour." Pergamon Press, Oxford. 549 pages.

B) Oehlers, D.J. and Bradford, M.A. (1999) "Elementary behaviour of Composite Steel and Concrete Structural Members". Butterworth Heinemann, Oxford, September, 256 pages.

C) Oehlers, D.J. and Seracino, R. (2004) "Design of FRP and Steel Plated RC Structures: retrofitting beams and slabs for strength, stiffness and ductility." Elsevier. 228 pages.

Papers

1) *Oehlers, D. J. and Johnson, R. P. (1981). "The splitting strength of concrete prisms subjected to surface strip or patch loads." Magazine of Concrete Research, 33, Sept., 116, 171-179.

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* not part of body of work for consideration for Doctor of Engineering

COMMENTARY OF RESEARCH

1. Introduction

In collaborative research, it is generally quite easy to distinguish who developed the numerical model, who designed the experiments and who developed the mathematics. However, it is often quite impossible to distinguish who first had the idea or *concept* as this often comes from close in-depth discussions where ideas are proposed, adapted and rejected until suddenly the *mechanism* or *concept* is understood. Hence no attempt will be made in this thesis to attribute the *concept* to an individual person. The writer of each paper is given in the references below as well as the co-authors' positions at the time of the research. Generally speaking when Oehlers is the first named author, he wrote the paper. Often when Oehlers is the second author and his post graduate (PG) is the first named author then Oehlers would probably have written the paper. The papers marked with an asterisk are not part of this Doctor of Engineering thesis.

In the following commentary, the major *concept* or idea that explains the mechanism is first described and it is shown that this can occur through tests, numerical simulations or simply visual models. Having identified the concept and, hence, an understanding of the mechanism, it will be shown how mathematical models can be developed which were not possible before the *concept* was understood. Often it will be shown how new concepts developed for a specific field of research can be applied to other fields of research. Of major importance in this thesis is both partial interaction behaviour and partial shear connection behaviour that is *partial action*. *Partial action* behaviour has been recognised for a long time in composite steel and concrete beams and further developments in this research field are described in both *Section 2: Splitting Mechanisms in Composite Steel and Concrete Beams* and *Section 4: Flexural Mechanisms in Composite Steel and Concrete Members*. What has not been recognised is its application to other diverse research fields such as the fatigue assessment of composite bridges in *Section 3: Fatigue Mechanisms in Composite Steel and Concrete Beams*, and intermediate crack debonding of plated structures and the ductility of hinges in reinforced concrete structures in *Section 5: Mechanisms in Composite Adhesively Plated Beams*.

2. Splitting Mechanisms in Composite Steel and Concrete Beams

2.1 Introduction

A mechanical shear connector in a composite steel and concrete beam transfers the shear from the steel to the concrete element by imposing concentrated loads onto the concrete element. As an example, a 19 mm diameter stud shear connector will exert a force of about 100 kN onto a bearing area of concrete about the size of a thumb. The dispersal of this force into the concrete element can cause the concrete to split releasing the triaxial restraint to the concrete under compression which may cause the concrete to crush and the connection to fail. The aim of this research was to quantify the splitting resistance of the concrete slab for any configuration of shear connectors.

2.2 Major Concept

Antisymmetric Transverse Stresses - Global Splitting

Splitting of concrete that is subjected to surface patch loads was understood at the time of this research mainly through research on the anchorage zone of post-tensioned members. It was often assumed that this could be applied to shear connectors embedded in concrete slabs which was shown in this research not to be the case.

Finite element analyses showed that the transverse forces induced by embedded concentrated loads forms an antisymmetric distribution of transverse forces as shown in Fig. 23(b) of Ref. 2 (1981). It was this new antisymmetric phenomenon that allowed the interaction of transverse forces from longitudinal lines of connectors, that is *global splitting*, and showed, surprisingly at the time, that the splitting forces in lines of connectors can be zero or significantly less than that of the individual connectors due to the interaction between compressive and tensile transverse forces.

The antisymmetric distribution of transverse forces was not expected from published research at the time. However in hindsight it could have been deduced logically. Take for example the symmetric prism in Fig. 23(a) in Ref. 2 with symmetric restraints at either longitudinal end; applying a longitudinal force at the centre of symmetry at point O must, for equilibrium, induce transverse tensile forces on one side and transverse compressive forces at the other side as in Fig. 23(b) Ref. 2. Furthermore, as finite element analyses do not distinguish between tension and compression but in positive and negative, then these distributions must be of exactly the same shape. It may also be worth mentioning that from this research can be seen the value of finite element analyses in forcing the researcher to think non-dimensionally. This is because one inputs numbers into the analyses that can apply to any system of measurement and, hence, it is the proportions between dimensions that matters and not their magnitudes.

2.3 Research Development after PhD

The fundamental principles that govern two-dimensional splitting were developed in my PhD research and published in Refs.1-3. Further research to allow for the three-dimensional dispersal of the concentrated force, sloping sides and the post-splitting resistance was required before it could be applied in practice.

The splitting resistance based on two-dimensional dispersal always gives a safe design which is often too conservative for practical use, particularly for shear connectors with limited side cover. Three-dimensional dispersal was allowed for in Ref. 8 which also showed the importance of transverse reinforcement in arresting the splitting crack and where the splitting research was developed into comprehensive design rules for any configuration of shear connectors and distributions of shear flow. Design rules were developed in Ref. 19 for shear connectors placed in longitudinal haunches with sloping sides which often occurs in practice.

Having now developed design rules for predicting the splitting resistance of shear connectors over a very wide range of configurations, it was felt necessary to determine the post-splitting resistance for situations where splitting could not be prevented. The effect of transverse reinforcement in maintaining some triaxial restraint to the compression zone was studied in Ref. 13. Rules were developed for most configurations of transverse reinforcement and, surprisingly although logically, it was shown that it is not the strength of the transverse reinforcement that matters but its stiffness. This knowledge further emphasises the difference between splitting in anchorage zones and splitting in composite beams. In the former, the bearing plate can be designed to substantially limit the compressive stresses so that if splitting occurs the transverse forces can be taken up by the transverse steel as concrete crushing can be designed against. In contrast, the bearing stresses in shear connectors have to be very large to achieve their dowel strength so that it would be uneconomical to limit the bearing stresses. Hence when splitting occurs in a composite beam, the transverse reinforcement is required to provide triaxial restraint to the compression zone through its stiffness.

2.4 Application outside research field

The research on splitting in composite steel and concrete beams started with the anchorage zone design of post-tensioned members, developed new approaches peculiar to composite beams and has now gone full circle where these new approaches are now applied in Ref. 28 to the analysis of anchorage zones.

Three dimensional dispersal of concentrated forces in composite beams is different to that in anchorage zones, because in composite beams the vertical dispersal is balanced by the axial force in the connector as the concrete-slab/steel-beam interface cannot take tension. Reference 28 allows for this difference in dispersal. Furthermore, in the previous research on splitting and in the design of anchorage zones, the ratio between the transverse force and longitudinal force for a line load was determined from finite element or photo-elastic analyses, whereas, in Ref. 28 this has been derived mathematically to give the true relationship.

2.5 Outcome

Generic rules have been developed for predicting the splitting resistance of the concrete slabs in composite steel and concrete beams. These can be applied to virtually any configuration of the shear connectors, any shear flow and even to slabs or haunches with sloping sides and now forms book chapters in Refs. A and B. Furthermore, rules have also been developed for the post-splitting resistance.

The splitting resistance and post-splitting resistance to shear connectors in composite steel and concrete beams are generic rules and can be applied to the design of the bolt shear connectors in bolted plated beams in Section 4.3 and to the anchorage zone of post-tensioned members.

2.6 References and Contributors

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[Ref. 1] *Oehlers, D. J. and Johnson, R. P. (1981). "The splitting strength of concrete prisms subjected to surface strip or patch loads." Magazine of Concrete Research, 33, Sept., 116, 171-179. Not part of D.Eng thesis.

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3. Fatigue Mechanisms in Composite Steel and Concrete Beams

3.1 Introduction

The fatigue design of the shear connectors in composite steel and concrete beams is often based on a full interaction analysis and in which the strength of the shear connection is assumed to be unaffected by cyclic loads until the fatigue life is used up. In this research, it is shown that the fatigue endurance of the shear connectors in a composite beam can be lengthened due to partial interaction. However, this benefit is offset by the fact that tests have shown that the static strength reduces as soon as cyclic loads are applied. The aim of this research was to quantify the interaction between the strength and endurance of shear connections to allow better estimations of the residual strength and residual endurance of vehicular composite bridge beams.

3.2 Major Concepts

Incremental Set

The fatigue endurance of shear connectors is usually determined from cyclic tests in which it is assumed that the static strength is constant over much of the test until rapid crack propagation causes failure at the end of the fatigue endurance. However, these same fatigue tests have shown that each cycle of load induces a permanent set as shown in Fig. 4 of Ref. 4 (1985) and Fig. 2 of Ref. 5 (1986). This permanent set per cycle or *incremental set* is a loss of energy that suggests a reduction in static strength due to crack propagation.

Asymptotic Fatigue Endurance

Fatigue cracks gradually propagate through a shear connector until the remaining strength is just sufficient to resist the static load after which failure occurs as in Fig.3 of Ref. 4 (1985). This illustrates the interaction between fatigue crack propagation and the static resistance for which a new approach of the *asymptotic fatigue endurance* was developed where the asymptotic endurance can be approached but never achieved.

3.3 Research Development

The reduction in strength of stud shear connectors due to cyclic loads was shown to occur in tests and through fracture mechanics and numerical simulations in Ref. 4. The concepts of the *incremental set* and the *asymptotic fatigue endurance* are first illustrated in this paper although not referred to in these terms. The paper directly links, through the *asymptotic endurance*, the residual endurance to the residual static strength, and also links the exponent of the fatigue endurance equation to the exponent of the crack propagation equation. Through these links, this paper forms the basis for a fundamentally new approach for the fatigue design and assessment of composite bridge beams.

The *incremental set* due to cyclic loads is quantified in Ref. 5 where it is shown that the exponent that occurs in both the crack propagation and the asymptotic endurance equations also applies to the incremental set. The static load/slip characteristics of stud shear connectors is also quantified. The effect of the incremental set and the load/slip characteristics on the behaviour of composite bridge beams is illustrated through numerical simulations in Ref.6 where, surprisingly, it is shown, and explained, why propped construction has a lower fatigue life than unpropped construction.

The *asymptotic fatigue endurance* depends on the static strength of the shear connector and, hence, accurate methods for predicting the static strength are required for accurate fatigue predictions. A new approach for deriving the static strength is developed in Ref. 7 which is also used to study the behaviour of push tests, as this affects the interpretation of the results, through the statistical concept of the minimum of a pair of results. Having accurately quantified the static strength, it was necessary to accurately quantify the asymptotic endurance; this was done in Ref. 10 through a statistical analysis of all available uni-directional push-tests, which was also used to recalibrate existing fatigue equations, and in Ref. 11 with new tests. The statistical results confirmed that the static strength and peak of the cyclic load significantly affected the fatigue endurance as indicated by the asymptotic endurance procedure. The incremental set and asymptotic endurance was studied further in Ref. 62 for bi-directional cyclic loading.

Having now quantified the fundamental fatigue material property of the shear connector, that is the *asymptotic fatigue endurance*, design and assessment procedures can now be developed. The basic asymptotic fatigue design equation is developed in Ref. 11, which is also used to clearly distinguish between existing fatigue design approaches and the new asymptotic approach, and an example of the design approach is given in Ref. 12. The asymptotic procedure is further advanced and refined in Ref. 20 where the concept of the *shear flow constant* is introduced and where the asymptotic approach is present in both its design form for new structures and its assessment form for existing structures. Further recommendations for design are made in Ref. 24.

The overall aim of this research was to develop fatigue design and assessment procedures for composite steel and concrete beams that were accurate because they simulated the actual behaviour within a composite beam. The research so far could accurately simulate the behaviour of the shear connector subjected to known shear forces. Through partial interaction theory and numerical simulations such as in Ref. 6, it was known that a full interaction analysis would overestimate the shear flows and hence give a safe design or assessment. However, to accurately simulate the behaviour of a composite beam and further improve the accuracy of the fatigue procedure, the beneficial effect of interface friction and partial interaction needed to be incorporated.

The effect of interface friction was derived in Ref. 40. Numerical simulations showed that the reduction in shear flow due to interface friction was not dependent on the distribution of the applied load but could be assumed to be uniform due to the rigid body displacement of the concrete slab. This allowed the asymptotic endurance procedure to be simply modified to allow for the benefits of friction. The effect of partial interaction was derived in Ref. 58 where a simple hand technique can be used to determine the benefit of partial interaction and an example of its incorporation into the asymptotic approach is given; this could only be achieved through the understanding of the new concept of the *partial interaction focal point* which is illustrated in Ref. 59. An application is given in Ref. 53.

It was now felt that the asymptotic fatigue analysis had been sufficiently refined to give a very good simulation of the actual behaviour of vehicular composite bridge beams. This was published in Ref. 59 as a tiered approach to allow the designer the freedom of different levels of accuracy.

3.4 Application outside research field

In much fatigue testing, the component is subjected to cyclic loads until it fails when its static strength reduces to that of the peak of the cyclic load. Frequently little attention is paid to when the static strength reduces and often it is assumed not to change until shortly before failure. The asymptotic approach developed for shear connectors was presented in a generic form in Refs.15 and 23 for different failure envelopes to place the emphasis of fatigue design more on the residual strength than on the fatigue endurance. The approach was further developed for welds in Ref. 25.

3.5 Outcome

A fatigue procedure for shear connectors in composite steel and concrete beams has been developed that directly links the static strength with the frequency of cyclic loads and also allows for the effect of interface friction and partial interaction. Hence the fatigue design of new bridges can now allow for the reduction in the static strength but of more importance the fatigue assessment not only determines the remaining endurance but also the remaining strength. This has allowed a tiered approach for assessment to be developed where it has been shown that simple existing techniques give a safe estimate and as the complexity of the analysis increases so does its accuracy. The research has been summarised in Refs. 45, A and B.

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4. Flexural Mechanisms in Composite Steel and Concrete Members

4.1 Introduction

The fundamental principles of elastic partial interaction theory in composite beams was first postulated by Newmark, Siess and Viest way back in 1952 and the fundamental principles of plastic partial shear connection theory by Yam and Chapman in 1968 and these principles laid the foundations for composite analysis and design. These principles are further advanced in this research.

In *Section 4.2: Composite Steel and Concrete Beams,* partial interaction is used to: quantify the slip in composite beams at failure; determine the reduction in the full-shear connection capacity due to partial interaction; and to develop an elegant hand procedure to allow for the effect of partial interaction. Partial shear connection analysis for beams with side profiled sheets is developed in *Section 4.3: Composite Encased Beams* and this approach is used and further developed for bolted plated beams which is a useful ductile form of retrofitting reinforced concrete beams. A new form of plating for the seismic retrofitting of columns is developed in *Section 4.4: Composite Plated Columns* where ironically it is shown that the plates have to remain elastic to achieve the greatest column ductility.

4.2 Composite steel and concrete beams

4.2.1 Major concepts

Mixed Analysis Approach

The realisation that the shear connectors achieve plasticity in a different zone to where the steel and concrete achieve plasticity, as shown in Fig.5 of Ref. 22 (1995), has allowed partial interaction theory to be used to develop the *mixed analysis approach* that can be used to derive the fundamental equations for fracture due to excessive slip of shear connectors in beams with partial shear connection.

Partial Interaction Focal Point

The realisation that two points on the bi-linear partial interaction strain profile remain constant for any degree of partial interaction, as shown in Fig.1 of Ref. 49 (2001), has allowed the development of the new concept of the *partial interaction focal point* which is useful in providing simple hand solutions for often very complex partial interaction problems.

4.2.2 Research development

Of concern in the design of composite beams with partial shear connection is premature fracture of the shear connector due to excessive slip. This is often prevented by limiting both the span of the beam and the degree of shear connection. A fundamental model was first developed in Ref. 22, which is used in Refs. A and B, and which was later referred to as the *mixed analysis approach* as it incorporates plasticity into an elastic analysis. Having developed the fundamental model in Ref. 22, this was extended for design to include non-linearities such as concrete cracking and plastic hinges in Ref. 47. The mixed analysis approach was further developed in Ref. 32 to allow for the interaction between partial shear connection and partial interaction and was also used and extended in Ref. 50 for the analysis of bolted plated structures.

For composite beams in which the concrete element is above the steel element, that is at different levels, analysis procedures do not have to consider directly the interaction between partial interaction and partial shear connection. The effect of this interaction is determined in Ref. 26.

Elastic partial interaction analysis is complex and has generally been restricted to simple beams with simple loading configurations. A major advancement was made with the discovery of the *partial interaction focal points* in Ref. 49 from which simple procedures were developed for determining the partial-interaction flexural stresses and in Ref. 59 for determining the partial-interaction shear flows. It is felt that these procedures will be useful tools in the fatigue assessment of vehicular composite bridges.

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4.3 Composite encased beams

4.3.1 Major concept

Encased partial shear connection

The rigid plastic ultimate strength analysis of encased composite beams, where the steel and concrete components are at the same levels as in Fig. 2(a) of Ref. 16 and Fig.1(b) in Ref. 27, required the realisation that full-interaction was synonymous with full shear connection as in Fig. 2(c) of Ref. 16 and Fig. 10(c) of Ref. 18 .

4.3.2 Research development

The procedures for determining the rigid plastic strength through partial shear connection analyses of composite beams in which the concrete element lay above the steel element were well established and show that partial interaction did not have to be considered directly. It was found that this approach could not be applied directly to encased composite beams where the steel and concrete elements are at the same level. A new approach was developed for composite profiled beams in Ref. 16 where it is shown that the full shear connection strength occurs with full interaction. Design procedures for partial shear connection as well as plate buckling are developed in Ref. 18 and the strength of the rib shear connectors in composite profiled beams in Ref. 57.

It was found that much of the research on composite profiled beams could be applied to the retrofitting technique of bolting plates to the sides of reinforced concrete beams. However in bolted plated beams the effect of transverse forces was found to be much more important, in Ref. 27, leading to partial interaction in both the longitudinal and transverse directions; the outcome of which is non-parallel strain profiles in the elements. Tests were performed in Ref. 42 which showed that standard partial shear connection analyses that ignored transverse partial interaction could not be used for bolted plated beams, so that in the companion paper in Ref. 43 new rigid plastic design procedures were developed. The mathematical interaction between transverse partial interaction and longitudinal partial interaction is established in Ref.50 which is also a further example of the mixed analysis approach. A review of plating that includes bolted plated structures is given in Ref. 51. The resistance to buckling of the bolted plated beams was established in Refs.33-37,41,46,48 and 65; my input into these papers was minor having given assistance to the experimental and application parts but they have been included as this was a grant funded collaborative research project between the Universities of Adelaide and New South Wales.

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4.4 Composite plated columns

4.4.1 Major concept

Cyclic partial interaction

It was realised that this new technique for seismic retrofitting reinforced concrete columns for ductility, shown in Fig. 1(a) of Ref. 63, could work only though partial interaction. In this case, it was necessary for the plate on the tension face to resist very little tensile force by opening up as in Fig. 1(c) of Ref. 63.

4.4.2 Research development

In the seismic retrofitting of RC frames it is often the requirement to increase the ductility of a column without increasing its strength. This can be done by wrapping the columns and confining the concrete which is a useful technique for circular columns but is less effective with rectangular columns. An alternative technique has been developed that does not rely on concrete confinement but on partial interaction to achieve ductility and the tests in Ref. 63 have shown that it works. The mathematical models for this new form of composite partial interaction structure were developed in Ref. 60 and the numerical simulation is described in Ref. 66.

4.4.3 Application outside research field

From the research on plated columns, a new approach for quantifying the ductility of unplated RC columns was developed in Ref. 67 where it was shown that additional longitudinal reinforcement can surprisingly increase the ductility of columns.

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4.5 Outcomes

New forms of partial interaction and partial shear connection theory have been developed for new forms of composite structures: composite profiled beams which are an additional use of profiled sheets; bolted plated RC beams that provides a ductile retrofit both in flexure and shear; and bolted plated columns that can increase the ductility of a column without increasing its strength. Partial interaction and partial shear connection theories have also been developed to prevent fracture of shear connectors due to excessive slip and also to quantify the changes in flexural stresses and shear flows due to partial interaction which can be used in fatigue assessment.

5. Mechanisms in Composite Adhesively Plated Beams

5.1 Introduction
Adhesive bonding steel or fibre reinforced polymer (FRP) plates to reinforced concrete structures is a relatively new form of retrofitting which is rapidly gaining in popularity due to both its ease of application and unobtrusive nature. However because the tensile strength of concrete is very low, these plates tend to detach prematurely and in a brittle fashion and, furthermore, there is much confusion and controversy as to the debonding mechanisms. The aim of this research has been to identify the debonding mechanisms, quantify the debonding mechanisms and quantify the ductility of plated RC beams; and in so doing provide designers with generic rules that can cover all situations and which can be used in conjunction with the bolted plated research in Sect. 4.3 to provide a range of plating techniques that can improve both the strength and ductility if necessary.

5.2 Plate end debonding
5.2.1 Major concept
Plate end (PE) debonding

The plate end debonding (PE) mechanism was identified in tests, Figs. 8-13 in Ref. 9 (1990), in which the plate end was terminated in a constant moment region so that it was not subjected to vertical shear, so that interface shear due to VAy/Ib was not present. As debonding propagated from the plate end inwards it was deduced that it was induced by curvature.

5.2.2 Research development
Plate end debonding in tension face plated beams was first identified and quantified in Ref. 9 where it was referred to as flexural peeling. The interaction between shear peeling, that is critical diagonal crack debonding, and plate end debonding was established through tests in Ref. 14. The debonding analyses for plate end debonding, critical diagonal crack debonding and their interaction for tension face plates were presented as design rules in Ref. 21 where the effects of creep and shrinkage were also developed.

The approach used to develop debonding rules for tension face plates was adapted to cope with plate end debonding of angle plates in Ref. 30; these rules were in effect the generic rules for plate end debonding. The generic approach was then applied to side plates in Ref. 38, adapted for compression face plates in Ref. C and shown to apply to FRP plates in Ref. 52. All of this research is published as generic design rules in Ref. C.

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5.3 Critical diagonal crack debonding

5.3.1 Major concept

Critical diagonal crack (CDC) debonding

The critical diagonal crack debonding (CDC) mechanism, shown in Fig. 1 of Ref. 9 (1990), is easy to recognise by engineers familiar with shear failure of beams or slabs without stirrups. It is simply the shear deformation across a critical diagonal crack that causes the longitudinal plate to debond, although, understanding of this mechanism would still appear to elude some researchers. However, it is now generally recognised by most guidelines.

Passive prestress

Realisation that the plate debonding force could be considered as equivalent to a passive prestress allowed the CDC debonding resistance to be established from prestressed code rules.

5.3.2 Research development

Critical diagonal crack debonding, of a tension face plate, was first identified in Ref. 9, where it is referred to as shear peeling, in order to differentiate from plate end debonding. Critical diagonal crack debonding tests were published in Ref. 14 where it was related to the concrete component of the shear capacity of the RC beam which is now standard practice in guidelines. The interaction between plate end debonding and critical diagonal crack debonding was also established by tests in this paper. A review of debonding mechanisms was published in Ref. 29. The use of side plates to inhibit critical diagonal crack debonding of tension face plates was illustrated in Ref. 31 and for the first time the intermediate crack (IC) debonding resistance of the plate was used in determining the enhanced shear capacity. This crucial link between intermediate crack debonding and critical diagonal crack debonding had now been established.

Through tests in Ref. 39, it was shown that critical diagonal cracks also induced debonding in side plated beams. This was important as it confirmed that generic rules could be developed, and were developed, for critical diagonal crack debonding as had already been established for plate end debonding. These tests also suggested a weak interaction between CDC debonding and PE debonding. Up to this stage of the research, the CDC debonding model was little more than purely empirical due to the complex problem of shear failure of RC beams. However, the realisation that research from Denmark on the concrete shear capacity of RC beams could be adapted for CDC debonding in Ref. 44 allowed mathematical models to be developed based on the CDC debonding mechanism and which was a major advance.

The research up to date was reviewed in Ref. 51 where tests also showed CDC debonding of FRP side plates. It was further established in Ref. 52 that the same debonding mechanisms, that is for both CDC and PE debonding, occurred in both steel and FRP plated specimens. It was confirmed by tests in Refs. 54 and 72 that the CDC debonding model could also be applied to angle plated beams and compression plated beams suggesting that it is a truly generic model. The lack of interaction between CDC and PE debonding of compression face plates was established in Ref. 61.

The models developed up to date converted the IC debonding force in the plate into an equivalent area of longitudinal reinforcement to determine the increase in the concrete component of the shear capacity due to plating, that is the CDC debonding resistance. This gave good results, although difficult to apply directly to FRP plates as FRP does not yield. Instead, the plate debonding force was shown to be equivalent to a prestress in Ref. 69. This allowed simple code rules to be used in Ref. 68 to derive the CDC debonding resistance and the use of an overall simple design procedure. This work has been published as a design procedure in Ref. C.

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5.4 Ductility and Intermediate Crack (IC) Debonding

5.4.1 Major concepts

Partial interaction hinge

The rotation capacity of reinforced concrete members is a complex problem. The clue to its understanding stems from the classical elastic/plastic moment curvature relationship as in Fig. 19(a) of Ref. 71 (2004). The horizontal ductile plateau is very difficult to accommodate in mathematical models as it requires a step change in the curvature at the point of maximum moment; this is an impossibility which leads to the convenient concept of hinges which does not fully solve the problem as the size of the hinge has to be defined. When a concrete flexural crack intercepts reinforcement an infinite strain is induced that must be relieved by interface debonding, hence, partial interaction must exist. It was this recognition of partial interaction within a hinge and the identification of the boundary conditions that allowed a solution to be found.

5.4.2 Research development

The rotation capacity of reinforced concrete beams has for a long time been an intractable problem and is becoming an increasingly important problem with the use of brittle reinforcing bars and brittle retrofitting techniques. Moment redistribution and intermediate crack (IC) debonding are closely related problems and there has been much good research published by others on IC debonding particularly in pull tests. However, even though some published papers purport that the intermediate crack (IC) debonding mechanism is a fracture mechanics problem, the analyses follow the partial interaction theory established years ago by Newmark, Siess and Viest.

The IC debonding of a plated corbel is shown in Ref. 17 which is an example of the application of plating prior to design rules being fully developed. References 56 and 64 show how IC debonding can form be part of a design procedure with CDC and PE debonding. References 51, 55, 64 and 70 illustrate through tests the brittle nature of RC beams particularly with externally bonded FRP reinforcement. These references mainly illustrate the importance of both quantifying IC debonding within a beam and its associated ductility or moment redistribution problem.

Current research in Ref. 73 tentatively established the boundary conditions required for the partial interaction IC debonding mechanism in plated beams. This research illustrated the partial interaction IC debonding mechanism and the concept of *partial interaction hinges* and also illustrated the importance of partial interaction in affecting the flexural rigidity and hence moment redistribution. The concept of equivalent flexural rigidities is developed in Refs. 71 and 74. The early part of this research is published in Ref. C.

5.4.3 Application outside research field

Whilst developing a partial interaction model for plated beams as in Ref. 73, it was realised that the intractable problem in reinforced concrete research that of the hinge ductility had to be first solved. Three major boundary conditions were identified in Ref. 75 which allowed a partial interaction numerical model to be developed that simulated the gradual formation and extension of hinges in reinforced concrete beams.

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5.5 Outcomes

This research has helped to identify the major debonding mechanisms which is really the first stage in developing safe design rules. It has also shown that these debonding mechanisms are generic as they apply to plates on any surface and because of this generic rules have been developed leading to the proposal of generic design approaches. Of particular significance is the development of the boundary conditions for the partial interaction hinges.

6. Summary

The civil infrastructure is both expanding rapidly and deteriorating so that an increasing proportion of the available resources are being channelled to maintain and upgrade the existing infrastructure. Hence there is an ever increasing demand for developing accurate methods of estimating the deterioration in order to extract as much as possible from the structure and also for developing inexpensive and unobtrusive retrofitting techniques. This has been the main thrust of my research.

Concepts: My main contribution to the advancement of the understanding of *mechanisms in composite structures* has been in the identification and quantification of the following major concepts:

- *antisymmetric transverse stresses; global splitting;*
- *incremental set; asymptotic fatigue endurance;*
- *mixed analysis approach; partial interaction focal point; encased partial shear connection; cyclic partial interaction;*
- *plate end debonding; critical diagonal crack debonding; passive prestress; partial interaction hinge.*

These new concepts have allowed mathematical models to be developed that closely simulate the real behaviour of the structure and, hence, allow more accurate design, assessment and analysis techniques.

Shear connection in composite beams: The research on the *static, fatigue and splitting behaviour of shear connectors* in composite steel and concrete beams provides design tools for the accurate assessment of the strength, stiffness and fatigue endurance of existing composite beams. It may be worth noting that shear connectors rarely cause failure directly. However, deterioration of the shear connection reduces the degree of interaction, thereby, increasing flexural stresses in both the steel and concrete elements. This in turn may reduce the fatigue life of the steel component particularly in hogging regions as well as cause additional cracking in the concrete component and subsequent deterioration. Hence a little more attention than is at present given to the initial design of the shear connectors may lead to the increased endurance of composite structures. All of this research has been published in two books.

Fatigue assessment of composite bridge beams: A tiered approach to the *fatigue design and assessment of composite bridge beams* has been developed which links the residual strength with the residual fatigue endurance as well as allowing for the effect of interface friction and partial interaction. This approach can be used to design new structures but more importantly it can be used to accurately assess existing structures beyond their original design life. This research has been published in two books. The recognition that the strength of shear connectors reduces immediately cyclic loads are applied has been incorporated into the assessment versions of the British steel standard for some time and very recently this concept has been included in the German standard. Although neither standard has taken the next step of allowing for the detrimental and beneficial effects of partial interaction.

Retrofitting reinforced concrete members by plating: The research on retrofitting by *adhesive bonding plates to flexural members*: identified and quantified two of the three major debonding mechanisms; advanced the understanding of the third through partial interaction approaches; determined the interaction between the three debonding mechanisms; and quantified ductility and moment redistribution and the effect of debonding on moment redistribution. Generic design rules have been developed for any plate material, for any geometry of plate and for plating any surface of the flexural member. These rules cover the flexural capacity, the shear capacity and the ductility of plated structures. The research on *retrofitting by bolting plates to flexural members* provides an alternative ductile retrofitting procedure to adhesive bonding plates; partial interaction and shear connection theories were used to develop design rules. The partial interaction and shear connection research on *bolting plates to columns* provides a much needed alternative technique for the seismic retrofitting of rectangular columns. This research has been published in a book.

My research started with composite steel and concrete structures where the major concern that differentiates composite structures from either steel or reinforced concrete structures is the mechanical bond at the interface between the elements of the composite structure. This interface behaviour had lead to the development of partial interaction and partial shear connection approaches specific to composite steel and concrete beams. I have further developed these approaches for profiled beams and for the fatigue assessment of composite bridge beams, taken it yet further beyond the established confines of composite structures to the analysis of plated columns and plated beams, and still further into the analysis of hinges in reinforced concrete beams.

LIST OF PAPERS ATTACHED

Please note: the paper reference number has been written on the right hand top corner of each page of the paper.

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