ANALYSIS AND SYNTHESIS OF EXTRNALLY PLATED REINFORCED CONCRETE BEAMS

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ABSTRACT:- Strengthening reinforced concrete (RC) beams by bonding steel or fiber reinforced polymer (FRP) on its tension face has become a popular retrofit method due to its rapid, simple and other advantages. However, debonding along the Steel-RC beam interface can lead to premature failure of the structures. Safe design of such a strengthened RC beam demands a reliable and predictive debonding strength model. This paper presents a careful finite element investigation into interfacial stresses in the adhesive layer bonding RC beam and soffit plate. Finite element modelling issues like proper selection of contact between adherents and symmetry conditions are first discussed, with particular attention on appropriate finite element meshes for the accurate determination of interfacial stresses. The interfacial stress behaviour at plate end has been analyzed for two cases of loading taken, one by applying uniformly distributed load and the other with a two point loading. Two special cases are considered in two point loading – for the case when the plate terminates with-in the constant moment region (CMR) and for the case when plate is extended beyond constant moment region where bending moment is minimal. The concentration of stresses in the adhesive layer near the plate end explained the significance in considering their influence in flexural debonding.

Keywords: interfacial stresses, flexural debonding, constant moment region, soffit plate, finite element method.

1. INTRODUCTION

1.1. General

Reinforced concrete structures often have to face modification and improvement of their performance during their service life. The main contributing factors are change in their use, new design standards, lack of maintenance practices, deterioration due to corrosion caused by exposure to an aggressive environment and accident events such as earthquakes.

The strengthening of reinforced concrete beams by bonding a soffit plate has become a popular retrofit procedure .This plate bonding technique has numerous advantages such as increasing the stiffness and strength of an existing flexural member with minimal impact on the surrounding environment. Considerable research has been undertaken on RC beams strengthened with a bonded soffit plate. Tests on RC beams bonded with either steel plates or fibre reinforced plastic plates have revealed that debonding of the soffit plate from the RC beam, typically with the concrete cover attached to the plate, is a common failure mode in these beams. This debonding failure mode is brittle and prevents the full utilization of the tensile strength of the bonded plate. It is therefore important to understand the mechanism of this debonding failure mode and develop sound design rules.

1.2. Bonding agent- adhesive

An adhesive is any substance that, when applied to the surfaces of materials, binds the surfaces together and resists separation. The use of adhesives offers many advantages over other binding techniques such as sewing, welding, bolting, screwing, etc.

These advantages include-

- The ability to bind different materials together.

- The ability to distribute stress more efficiently across the joint.

- The cost effectiveness of an easily mechanized process.

- An improvement in aesthetic design.
- Increased design flexibility.

Disadvantages of adhesive use include- decreased stability at high temperatures, relative weakness in bonding large objects with a small bonding surface area and greater difficulty in separating objects during testing.

1.3 METHODS AND MATERIALS USED FOR FLEXURAL STRENGTHENING

1.3.1. Using Ferro-cement laminate

Ferro cement is a thin composite material which is composed of cement mortar reinforced with uniformly distributed layers of continuous, relatively small diameter, wire meshes. Ferro-cement, being of the same cementitious material as reinforced concrete (RC), is ideally suited as an alternative strengthening component for the rehabilitation of RC structures. It possesses higher tensile strength to weight ratio and a degree of toughness, ductility, durability and cracking resistance that is considerably greater than those found in conventional cement based materials. The ferro cement was utilized for its toughness, cracking resistance and ease of application to fit the difficult contours of structures. For strengthening beams in flexure pre-fabricated ferro cement reinforcements were attached onto the beams tension face before the ferro cement matrix was cast to complete the laminate. The beams strengthened without surface roughening and without using the mechanical shear connectors' exhibits localized horizontal cracks along the concrete/ferro cement interface and severe de-lamination of the ferro cement at failure.

1.3.2 Using externally bonded plates

Externally bonded steel plates and polymer composites are more significant materials regarding flexural strengthening purpose. Primarily steel plates were used for strengthening and repairing of RC members. The use of advanced composite fibre materials as external flexural reinforcement of concrete and other structures has progressed well in the past decade in selective applications where cost disadvantage is outweighed by a number of benefits such as corrosion resistant, low maintenance requirement, impact resistant, non-conductive and non-metallic, fire retardant, light weight and long life span. Steel and FRP plates are bonded by using epoxy resins in the tension face of the beam. The main fibre types used are carbon (CFRP), glass (GFRP) and aramid (AFRP). Carbon fibre reinforced polymer (CFRP) has relatively low modulus of elasticity and linear stress strain relationship up to rupture with no definite yield point (ISIS Educational Model 4, 2004).

1.3.3 Using near surface mounted (NSM) slits/bars

The near surface mounted (NSM) reinforcement technique consists of placing the FRP reinforcing bars or strips into pre-sawn grooves in the concrete cover in the tension region of the reinforced concrete members and are bonded to the three sides of the groove using high strength epoxy adhesive or cementitious grout. Configuration of the FRP reinforcements used for the NSM technique is controlled by the depth of the concrete cover. After installation, the NSM FRP reinforcements are protected against mechanical damage, wear, impact, and vandalism. This technique can also provide better fire resistance in the event of a fire. Therefore, it could reduce the cost of fire protection measures.

1.4. INTERFACIAL STRESSES

From afore mentioned methods of flexural strengthening, strengthening of beams by external plate bonding is considered in the present study. Two interfaces are considered in this method, one along the concrete to adhesive (AC) interface and the other along the plate to adhesive (PA) interface. The tensile stresses are to be transferred from the bonded plate to the concrete through the adhesive layer leading to the development of very high normal and shear stresses near plate end along the two interfaces. The stresses thus developed in these interfaces are called interfacial stresses; they play a predominant role in understanding the failure mode of the plated beams.
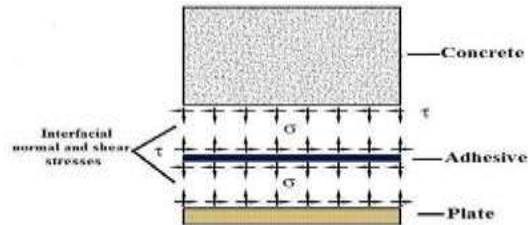
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Figure 1.1 Typical views of interfacial stresses between AC and PA interfaces

1.5 MODES OF FAILURE

The plate end debonding (PED) failure initiates at or near the plate ends. It appears in different modes.

- ✓ Concrete cover separation which occurs at the level of the steel tension reinforcement starting from a plate end.
- ✓ Interfacial debonding at the adhesive interface which occurs usually in the concrete at a small distance from the adhesive-concrete interface.
- ✓ Mixed mode with a combination of (1) and (2).
- ✓ Critical diagonal crack (CDC) initiated concrete cover separation.
- ✓ Critical diagonal crack (CDC) initiated interfacial debonding.
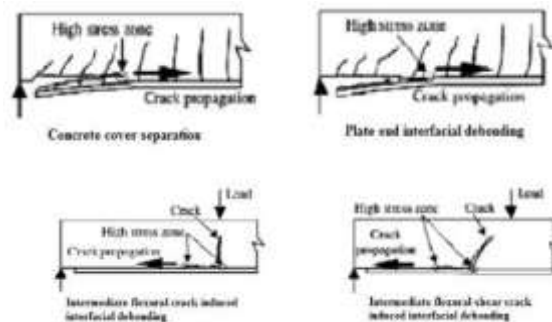
Figure 1.2 Failure modes observed in externally plated RC beams.

1.6. METHODOLOGY IN CONCISE

The analytical investigation process essentially consists of following

1) Identification of Parameters

2) Finite element modeling of externally plated RC beam

3) Finite element mesh modelling and convergence study.

4) Analysis of interfacial stresses in adhesive layer.

5) Results & Discussions

1.7. OBJECTIVE AND SCOPE OF WORK

The present study aims to investigate the debonding failure pattern of bonded plate that helps to propagate a predictive model by analyzing the interfacial stress distribution along the adhesive in externally plated RC beams using Finite

Element computer program ABAQUS. In this study a simply supported RC beam strengthened by bonding a soffit plate is analyzed under uniformly distributed loading and two point loading conditions.

The main objective of the study is:

- ✓ To study on the stress distribution along the interface for different geometric properties of plates and adhesive layer.
- ✓ To compare the test results of beams that are bonded with steel plates and Fiber Reinforced Polymer plates.
- ✓ To study on the stress distribution along the interface with respect to position of plate termination.

2. LITERATURE REVIEW

Mohammed Raoof et al. (1998) have done a theoretical and experimental study on externally plated RC beams by using theoretical parametric studies, based on a recently proposed model, the influence of various design parameters such as concrete cube strength, size and position of main embedded tensile bars, width of the beam, plate thickness, and ratio of plate/beam width, on the magnitude of ultimate plate peeling moment are investigated and some aspects of the theoretical predictions are checked against large scale test data reported by others. The question of pre-cracking of the beams prior to upgrading them with externally bonded steel plates is discussed in some detail. It is theoretically shown that testing uncracked (i.e. as cast) beams provides results which may reasonably safely be used for predicting the behaviour of actual beams in practice which (under service conditions) are invariably pre-cracked to some degree.

Boucif Guenaneche, Abdelouahed Tounsi et al. (2013) studied on effect of shear deformation on interfacial stress analysis in plated beams under arbitrary loading. An improved theoretical analysis of the interfacial stresses is presented for a simply supported plated beam subjected to arbitrary loading. The solution is based on the deformation compatibility approach where both the shear and normal stresses are assumed to be invariant across the adhesive layer thickness. Indeed, the distribution of shear stress through the thickness of adherents is obtained by solving the equilibrium equations of stresses. The shear stresses, thus obtained, are shape parabolic through thickness of the adherent. The effect of shear deformation on the variation of interface stresses along the reinforcing plate is illustrated by a numerical example to demonstrate the advantages of the current solution. The solution is general in nature and may be applied to the analysis of others composite structures.

3. FINITE ELEMENT MODELLING AND ANALYSIS

3.1 GENERAL

This paper describes how to do modelling and analysis using ABAQUS. It includes geometry modelling, property and section assignment, assembling, meshing, defining boundary conditions, defining interactions, and analysis.

3.2 MODULES IN ABAQUS

3.2.1 Part Module

It is used to define the geometry of the individual components of the model. We can create parts that are native to ABAQUS/CAE, or we can import parts created by other applications either as a geometric representation or as a finite element mesh.

3.2.2 Property of Materials

We have to define the properties of a part through sections. Once completion of creating a section, we can use one of the following two methods to assign the section to the part in the current viewport:

- ✓ By simply selecting the region from the part and assign the section to the selected region.
- ✓ By using the set toolset to create a homogeneous set containing the region and assigns the section to the set.

3.2.3. Assembly of Parts

Each part that we created is oriented in its own coordinate system and is independent of the other parts in the model. Although a model may contain many parts, it contains only one assembly. We have to define the geometry of the assembly by creating instances of a part and then positioning the instances relative to each other in a global coordinate system.

3.2.4 Analysis Step

There are two kinds of analysis steps in ABAQUS: general analysis step, which can be used to analyse linear or nonlinear response, and linear perturbation step, which can be used only to analyse linear problems.

3.2.5 Loading Conditions

In ABAQUS the term load generally refers to anything that induces a change in the response of a structure from its initial state, including:

- ✓ Concentrated forces,
- ✓ Pressures,
- ✓ Nonzero boundary conditions,
- ✓ Body loads, and
- ✓ Temperature (with thermal expansion of the material defined).

3.2.6. Boundary Conditions

Prescribed conditions, such as loads and boundary conditions, are step dependent, which means we must specify the step or steps in which they become active. Once we have defined the steps in the analysis, we can define prescribed conditions. To apply a prescribed condition to a region, we can either select the region directly in the viewport or apply the condition to an existing set. Creating Sets are convenient tool that can be used to manage large complicated models.

3.2.7 Meshing

Basic meshing is a two-stage operation:

- ✓ Seeding the edges of the part instance
- ✓ Meshing the part instance.

We have to select the number of seeds based on the desired element size or on the number of elements that we want along an edge, and ABAQUS/CAE places the nodes of the mesh at the seeds whenever possible.

3.3 Finite Element Description of model

Geometric modelling of RC beam, Adhesive layer and soffit plate has been done separately using the part module. The material behaviour was assumed to be homogeneous and isotropic. The material properties such as elastic properties were assigned using the property module. Only a quarter model is prepared to analyze due to constraints in computational resources. The externally plated RC beam model is discretized into a mesh consisting of C3D8R element – An 8-node linear brick Element with Reduced integration. Each node has six degrees of freedom.
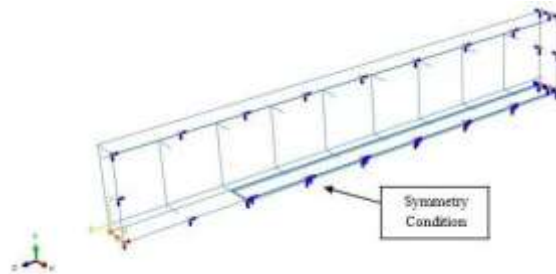
Figure 3.1 Typical details of symmetry conditions along x and z axes

3.4. Loading conditions

In the present study the plated RC beam is analysed under uniformly distributed loading condition and two-point loading condition. The load is applied along the span of the beam as pressure over the top surface for UDL and two-point loading is given like total load on two extruded surfaces over the beam where loading has to be done. Three cases are considered and models are created accordingly.

Case-1: Externally plated RC beam subjected to uniformly distributed load. Case-2: Externally plated RC beam subjected to two-point loading with plate terminated within the constant moment region.

Case-3: Externally plated RC beam subjected to two- point loading with plate extended beyond the constant moment region to a point where bending moment is minimal.

3.5. Element type

The element type chosen is C3D8R. C3D8R is an 8- node linear brick element with reduced integration. It has six degrees of freedom at each node. They are translations in x, y and z directions and rotations about x, y and z axis. C3D8R elements can be used in three-dimensional analysis. In ABAQUS/Standard they use linear or quadratic interpolation and allow mechanical and thermal (uncoupled) loadings. These elements can be used in static and dynamic procedures. These elements uses reduced (lower order) integration to form the elements stiffness. Reduced integration usually provides more accurate results and significantly reduces running time, especially in three dimensions.
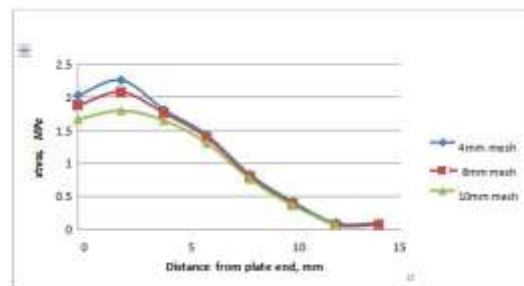
3.5 MESH CONVERGENCE STUDY

Meshing is an important part of finite element analysis. In the process of analysis special attention should be given to mesh the model in the best way possible. The same model can be meshed using different elements size. The aim is to find the most appropriate and efficient element size to do the analysis. Finding the most appropriate and efficient mesh is highly dependent on the computational resources, because as the mesh gets finer more computational resources are needed for the analysis. So the computational capability of the computer is one of the main factors in order to determine the mesh density.

Mesh convergence study is done on the RC beam model which is used for the validation. Selecting an optimum mesh is very much needed especially in the present study since the basic assumption made is that the concentration of interfacial stresses is more near the plate end, a very fine mesh is to be needed to observe the stress variation.

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Table 3.1 Mesh Convergence Study for interfacial stresses

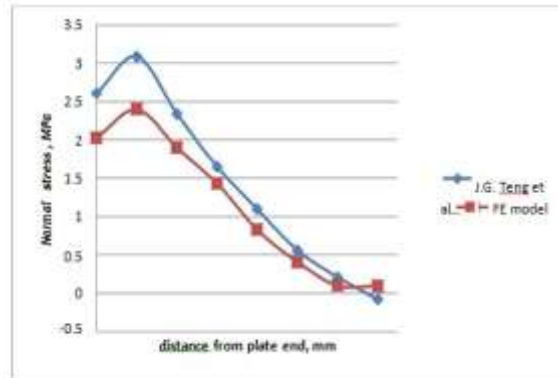| Distance from plate end in mm	Stresses in MPa 4mm mesh	Stresses in MPa 8mm mesh	Stresses in MPa 10mm mesh
0	2.03	1.88	1.68
2	2.26	2.08	1.80
4	1.81	1.76	1.65
6	1.43	1.39	1.31
8	0.83	0.8	0.76
10	0.41	0.39	0.36
12	0.1	0.07	0.064
14	0.096	0.065	0.06

Figure 3.3.Mesh convergence study

The boundary conditions adopted for the plated beam is simply supported. It is subjected to a uniformly distributed load of 15N/mm. The material properties of validating model are given in table 3.2.

Table 3.2 Properties of validating model

Component	Width, mm	Depth, mm	Length, mm	Young's modulus, MPa	Poisson's ratio
Concrete	100	150	2400	20000	0.17
Adhesive	100	4	1800	2000	0.25
Steel Plate	100	4	1800	200000	0.3

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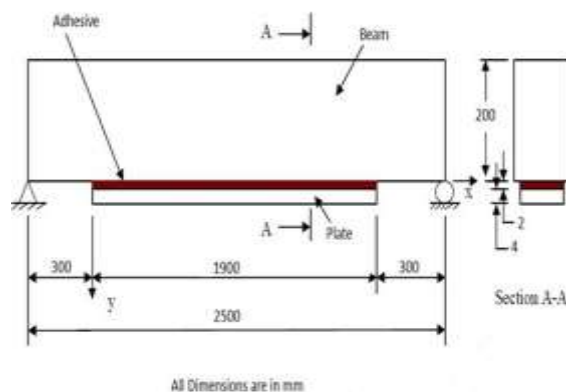**Figure 3.5 Interfacial stresses near the plate end.**

Figure 3.5 explains from observation that the stress pattern near the plate end for the finite element model created for validation in the present study is almost similar to that of the stress behaviour obtained by J.G. Teng et al and there was a little percentage error in the result values due to selection of bigger mesh by considering the computational resource constraints. Since, the mesh size considered by J.G. Teng et al is 0.4mmx0.4mm where as it is 4mmx4mm for the finite element validation model.

3.6. PRESENT STUDY

The material properties given in table 3.3 have been used to create the model for analyzing the interfacial stresses in the adhesive layer. The boundary condition adopted is simply supported.

The behaviour of interfacial stresses has been investigated by considering the effect of various geometric and mechanical properties of the adherents. Major two cases considered in the present study are the behaviour and influence of interfacial stresses near the plate end for the cause of failure when the beam is subjected to uniformly distributed load and two-point loading. Further, two cases are considered in two-point loading, for the plate when terminated within the constant moment region and the plate extended beyond the constant moment region where the bending moment is minimal.

Finite element model of externally plated RC beam is developed in ABAQUS to study the interfacial stress behaviour in the adhesive layer near the plate end. All the elements are modelled with C3D8R linear brick element. The typical finite element model of the plated beam is shown in the figure 3.8.

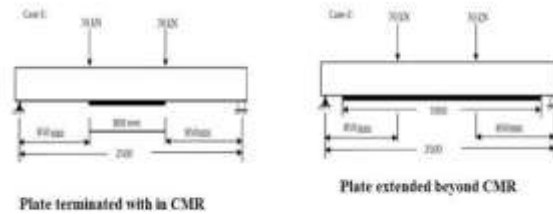**Figure 3.6 Typical view of a plated RC beam subjected to UDL**

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Figure 3.7 Cases considered in plated RC beam subjected to two-point loading
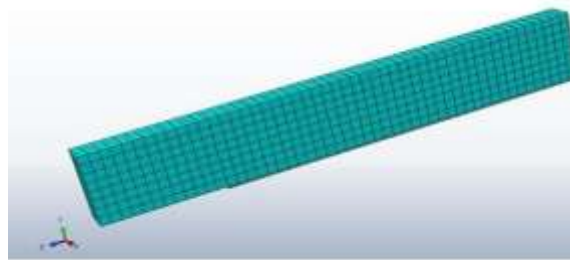
Figure 3.8 Typical finite element model of the plated beam

Parametric study is carried out with different geometric properties and different soffit plate material. The step analysis considered in the present study is static general. The material properties used in the present study are given in table 3.2.

Table 3.3 Properties of present model

Component	Width, mm	Depth, mm	Length, mm	Youngs modulus, MPa	Poisson's ratio
Concrete	130	200	2500	30000	0.2
Adhesive	130	2	1900	2000	0.35
Steel Plate	130	4	1900	200000	0.3
CFRP	130	2	1900	138000	0.21

4.0. RESULTS AND DISCUSSIONS

4.1 GENERAL

A three dimensional finite element model of externally plated reinforced concrete beam is developed with the material properties mentioned in table 3.3 using ABAQUS. In the present study, importance is given mainly to understand the behaviour of interfacial stresses near the plate end.

4.2 PARAMETRIC STUDY

A parametric study is presented here in which finite element interfacial normal and shear stress behaviour are compared when one of the parameters was varied each time with all the other values as given in Table 3.3 unless otherwise stated to give a more comprehensive assessment of the performance of the plated beams. The beam of Figure 3.6 was taken as the reference beam.

The parameters varied in the present study include-

- ✓ The adhesive layer thickness
- ✓ The adhesive layer elastic modulus
- ✓ The soffit plate thickness
- ✓ The soffit plate material

4.2.1 Loading

Two loading conditions are considered in the present study-

A **uniformly distributed load** of 50KN/m is applied along the length of the beam as shown in Figure 3.6 and the parameters are varied in this loading condition alone.

Two-point loading of 30KN at each point is applied on the beam by maintaining the dimensions of concrete adherent constant and by varying the length of plate, one by terminating plate within the constant moment region and the other by extending plate beyond CMR where bending moment is minimal as shown in Figure 3.7.

4.2.2 Effect of Adhesive layer thickness

Interfacial normal and shear stresses were obtained for four different adhesive layer thicknesses of 1, 2, 3 and 4 mm with all other properties as given in Table 3.3. Both the interfacial normal and shear stresses are shown in Figures 4.1 and 4.2 respectively for the region near the plate end.
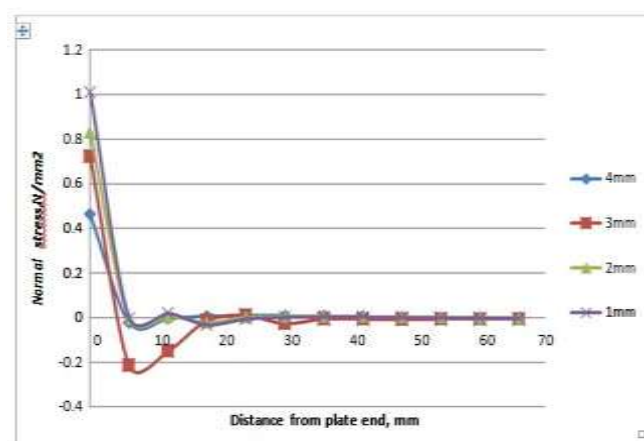

Figure 4.1 Effect of adhesive layer thickness on interfacial normal stress

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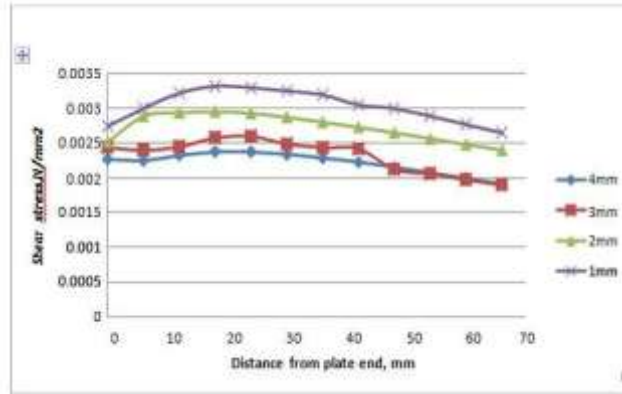

Figure 4.2 Effect of adhesive layer thickness on interfacial shear stress

It can be seen that reducing the thickness of the adhesive layer leads to an increase in both the normal stress (Figure 4.1) and the shear stress (Figure 4.2). The peak interfacial normal stress occurs near the end of the plate. At the end of the plate, the interfacial shear stress values are slightly tending towards zero. The peak finite element shear stress occurs at a short distance from the end of the plate, rather than at the end of the plate.

Table 4.1 Peak interfacial stresses for different adhesive layer thickness

Adhesive thickness, mm	Peak stresses, MPa
1	1.02
2	0.83
3	0.72
4	0.46

4.2.3 Effect of adhesive elastic modulus

The effect of varying the elastic modulus of the adhesive is shown in Figures 4.3 and 4.4. As the elastic modulus of the adhesive is increased, the interfacial normal and shear stresses also increase.
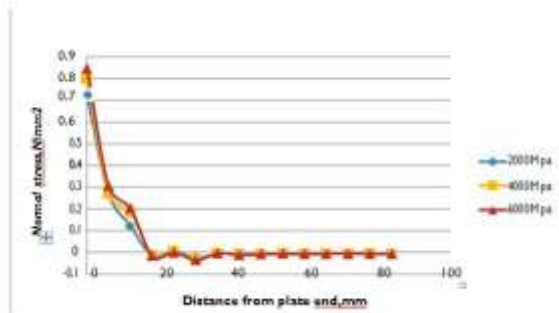

Figure 4.3 Effect of adhesive elastic modulus on interfacial normal stress

The plate length considered in case-1 is assumed to be 800mm, while all the other properties are as per mentioned in table 3.3. It is observed that the peak stresses are obtained near the plate end in both the cases; stresses are highly increased near the plate end in the case where plate is terminated in CMR when compared to case-2. Figure 4.10 and 4.11 shows the stress contours for case-1 and case-2 respectively.
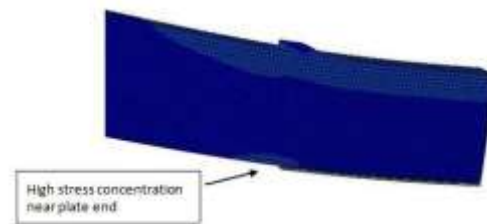
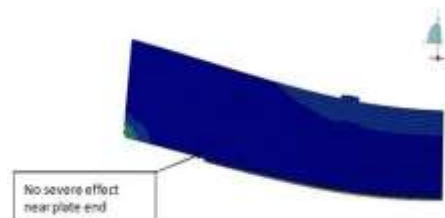**Figure 4.10 Stress contour when the plate is terminated within CMR**

Figure 4.11 Stress contour when plate is extended beyond CMR

4.3 STRESS CONTOURS

The observation of stress contours helps to understand the interfacial stress behaviour very easily. The most common pattern of the stress contour has been observed in almost all the cases in the present study with the stresses starting high near the plate end and gradually decreasing along the length of plate. Figure 4.12 and 4.13 shows the stresses observed in adhesive layer.
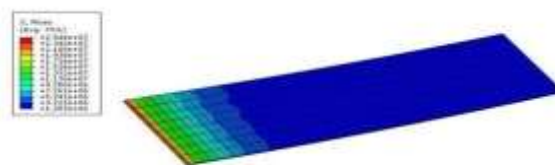
Figure 4.12 Stress contour of adhesive when plate is terminated in CMR
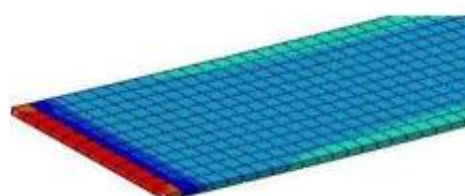
Figure 4.13 Stress contour of adhesive layer for beam subjected to UDL

5.0. CONCLUSIONS

5.1. SUMMARY

A careful finite element investigation into interfacial stresses in reinforced concrete (RC) beams strengthened with a bonded soffit plate has been dealt in the present study. The present study was focused on the behaviour of interfacial shear and normal stresses in the adhesive layer near the plate end. The parametric study is done when one of the parameters was varied each time with all the other values as given in Table 3.3 unless otherwise stated to give a more comprehensive assessment of the performance of the plated beams when they are subjected to uniformly distributed load. Another loading condition is also considered in the present study i.e. to assess the influence of the position of plate termination on the interfacial stresses under two-point loading.

5.2. CONCLUSIONS

Based on the results of finite element analysis, the following conclusions are derived.

- ✓ In general, it is observed that, Uniform stress distributions in the adhesive layer as assumed in early existing approximate analytical solutions are found at a small distance away from the end of the plate.
- ✓ To analyze externally plated RC beams for accurate determination of the interfacial stresses, a very fine mesh has to be used so that the effect of any further mesh refinement is reduced to a zone near the end of the plate.
- ✓ Finite element results showed that stresses vary strongly in the adhesive layer, in particular near the end of the plate.
- ✓ Under the action of uniformly distribute load, the following conclusion are derived from the parametric study.

The interfacial stresses were found to increase with a reduction in adhesive layer thickness, and peak stress values are obtained near the plate end then the stress distribution is almost uniform a little away from end of the plate.

- ✓ The interfacial stresses were found to increase with an increase in adhesive elastic modulus and plate thickness.
- ✓ The effect of adhesive elastic modulus haven't shown any significant variation in adhesive stresses whereas, the variation in adhesive thickness have shown significant influence on stress distribution particularly near the plate end.
- ✓ The replacement of CFRP to steel plate has shown a considerable amount of reduction in peak stresses.
- ✓ Under the action of two-point loading
- ✓ Termination of plate within the constant moment region is resulting to very strong variation in stresses near the plate end and the peak values are high compared to case of which plate extended beyond CMR.
- ✓ It is found feasible to terminate plate at a position where bending moment is minimal for a better performance of the beam.

Further parametric studies in this case and consideration of shear deformation effect helps for complete assessment of stress distributions.

By considering all the above conclusions and existing design a predictive model can be prepared in practical approach which helps for better performance of structure.

5.3. FUTURE SCOPE OF WORK

An experimental approach is to be carried out with the specifications of analytical model used in the present study.

- ✓ Comparative studies are to be done for Finite element model and experimental model.
- ✓ Consideration of shear deformation effect on interfacial stresses has a great scope in future work.
- ✓ Values thus obtained are to be verified with the existing analytical solutions and conclusions can be declared on the interfacial stress influence on failure modes.

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