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Dynamic response of cracked concrete rehabilitated with composites

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ABSTRACT: Disaster mitigation is one of the ongoing efforts in most of the countries to reduce the impact on people and property. The focus of the present study is to provide design inputs for rehabilitating beam structures using locally available composite materials based on linear and nonlinear dynamic analysis. This study models the tensile zone of a beam structure using finite elements with pre-assigned crack widths and crack depth. In linear modeling, the stiffness is assumed to vary linearly and in nonlinear modeling, bilinear variation of the stiffness is considered for analysis. The linear and non-linear response of cracked beam obtained from the finite element method is given as input for dynamic analysis. The frequency, time-period shift and amplitude are studied for uncracked beam, beams with damage for different types of cracks width and depth and design recommendation for rehabilitation of damaged beam with different types of composites are suggested.

1 INTRODUCTION

Concrete is a compound material where aggregates are randomly placed within the cement paste. The internal structure of concrete is non-homogeneous and complex due to the randomness of aggregate arrangement. But if the concrete is considered as a homogeneous material, its behavior under loading cannot be understood properly. In fact, assumption of material homogeneity in the analysis of concrete cracking leads to unrealistic results. (Shahbazi and Rasoolan, 2017). This paper studied the change in geometry leaves a significant effect on the stiffness of the material. In linear modeling, the stiffness is assumed to vary linearly i.e., the restoring force was proportional to the displacement. In nonlinear modeling, stiffness is assumed to be varying nonlinearly. A bilinear variation is considered in this paper, assumed to be constant till yield and beyond yield point it changes.

Dynamic non-linear analysis is difficult and time consuming compared to static non-linear analysis. So, in practice dynamic non-linear analysis is not attempted instead a quasi-static approach of equivalent response is done. In this paper the stiffness obtained from static nonlinear analysis is given as input for dynamic nonlinear analysis in a quasi-static sense for cracked material and later using equivalent SDOF model. For this purpose, various model with different crack opening and young’s modulus were analyzed using fracture mechanics’ approach.

2. TRENDS IN FRACTURE OF QUASI-BRITTLE MATERIALS

The research activity in fracture mechanics of quasi-brittle materials of concrete, rocks, ceramics, composites, ice, and ice polymers experienced a burst of activity during the 1980’s. Recently, it is being recognized that fractures of concrete and of modern toughened ceramics exhibit strong similarities (Bazant and Planas, 1998; Carpinteri et al., 2002; Vikas and Chandra Kishen, 2008). Their exploitation should benefit both disciplines. In fact, the way to toughen ceramics is to make them behave more like concrete, especially reinforced concrete. At present, the introduction of fracture mechanics into concrete design is becoming important. This helps to achieve a uniform safety margin, especially for structures of different sizes. In specific, applications of fracture mechanics are most urgent for structures such as concrete dams and nuclear reactor vessels or containments, for which the safety concerns are particularly high and the consequences of a potential disaster enormous.

3 DYNAMIC NON-LINEAR ANALYSIS

The mathematical definition of nonlinearity contains two important features:

1. A small change in input may produce an incommensurably large change in response.
2. The superposition principle does not hold

There are two methods to explain: One method is to compare a non-linear system to a linear system like a vibrating violin string. The vibrating string has a motion that is the sum of many simpler contributing motions, the harmonics of the string. The motions involved in non-linear systems are not simply combinations of much of simpler motions. The second method is to look at the response of a non-linear system to vibrating input. A linear system always responds by vibrating at the same frequency as the input. A non-linear system does not usually or necessarily respond at the same frequency as the input (Chopra, 1995).

The second method is adopted in this paper. Normally the dynamic non-linear analysis is very difficult and time consuming compared to static non-linear analysis. So in practice, mostly dynamic non-linear analysis was ignored. Research are going on to make the dynamic nonlinear analysis easier (Pinho, 2007; Merter and Ucar, 2013). In this paper the dynamic nonlinear analysis was carried out by using the results obtained from static nonlinear analysis of cracked material using finite element software package.

The material properties of the system, stiffness includes different form of non-linearity. In linear modeling, the stiffness is assumed to vary linearly i.e., the restoring force was proportional to the displacement. In nonlinear modeling, stiffness is assumed to be varying nonlinearly. A bilinear variation is considered, assumed to be constant till yield and beyond yield point it changes. The linear and non-linear response of cracked specimen is obtained from the finite element software package ANSYS 12.0 and is given as input for dynamic analysis. The package NONLIN 8.0 is used to obtain the dynamic response of the concrete and composite subjected to impulsive force.

4 METHODOLOGY AND MODELING

Cracking in plain concrete and reinforcement beams can be done in two ways, one by using fracture mechanics and another by reducing material property (Young’s modulus or modulus of elasticity). The fracture mechanics approach is an accurate method which involves real cracking in the beam compared to the other method mentioned above. For plain concrete, the crack will progress up to centre whereas for reinforced concrete it will stop at reinforcement level. So crack length is not limited in plain concrete beams (Carlos et.al, 2021). In this paper, deflection and stress intensity factor are found out for specimen or model with different crack width, crack depth and modulus of elasticity under tension. First the nonlinear stiffness assessed based on static analysis for different cracked and uncracked specimens with material nonlinearity. Then studied the frequency, time-period shift, amplitude and then design recommendation for rehabilitation of damaged beam is suggested.

Finite element method is used to do the fracture analysis and it will accommodate complex geometry and boundary conditions. Also, it is used to represent various types of complicated material properties that are difficult to incorporate into other numerical methods. ANSYS is a complete finite element analysis package and is used in this research to study the nonlinear static analysis of beam by changing the material property of the cracked /damaged beam.

A concrete beam with a crack is taken for analysis, in which the length and depth of the beam is assumed to be 3000 mm x 300 mm. The crack is assumed to be located in the tensile region and a part of the region is taken for fracture analysis in which D_c represents the depth of the crack and C_o represents the crack opening. The length and depth of the model taken for analysis is 80mm x 20mm respectively.

Three different parameters have been considered for analysis, they are depth of the crack, crack opening or width of the crack, damages and intensity of load. The depth of the crack is represented in ratio with respect to the depth of the model and is varied from 0.1 to 0.5 with an increment of 0.1. Width of the crack or crack opening is varied as 0.001, 0.01, 0.1, 1.0 mm. For all the above cases the material is assumed to be undamaged or damaged to 20% or damaged to 50% respectively. The grade of concrete used for the analysis is M 30.

After the beam have been cracked or damaged, composites have been introduced and their behaviour is studied for different width and depth of the crack. Here the composites are represented in terms of the young's modules of the concrete (Ec). The composites may be in the form of fibres or graded fine aggregates like sand or silica fume and thereby it is represented as the ratio of the young's' modulus of the composite (Ecc) to the young's' modulus of the concrete of grade M30 (Ec) and are ratios adopted in this work are 1.2, 1.5 and 2.

Consider a beam element with two nodes I and J as shown in Figure 1 with a damage at a distance of from x_1 distance and spread of damage is x_2. Length of the beam element is L and its flexural rigidity is EI. Then is divided into three sub-elements, two elements without crack and one middle element with crack as shown in Figure 2.

The element used for creating the concrete model with a crack in ANSYS 11.0 is PLANE 82 This element has eight nodes having two degrees of freedom at each node that is translations in the nodal x and y directions. It provides more accurate results for mixed (quadrilateral-triangular) meshes. It can tolerate irregular shapes without as much loss of accuracy. This element has compatible displacement shapes and is well suited to model curved boundaries and has plasticity, creep, swelling, stress stiffening, large deflection and large strain capabilities (Yazdizadeh, 2010)

Rectangular and singular elements are used for meshing. Rectangular elements of size (1x 1) are used throughout the model except near the crack region. Near the crack tip the variation of stress is very high. In order to get accurate results, singular elements are used near the crack tip. They are skewed at quarter points (1/4 pts). This type of meshing is very useful for modeling stress concentrations near the crack tips. The model is subjected to tensile stress staring with an intensity of 0.25 N/mm^2, and and the iteration stopped once the solution is converged.

The package NONLIN 8.0 is used to obtain the dynamic response of the concrete and composite subjected to impulsive force. NONLIN 8.0 is a Microsoft windows-based application for the dynamic analysis of single degree of freedom structural systems. This program uses a step-by step method to solve incrementally nonlinear equation of motion. The stress strain values obtained for uncracked case, damaged/cracked cases and rehabilitated cases from static analysis are listed in Table 1.

Primary stiffness calculated from the static linear analysis for concrete and composite (Shifana, 2009) is given as the input for dynamic linear analysis. The load deflection behvaiour of the concrete and composite is modeled as bilinear with primary and secondary stiffness and a typical plot for linear and nonlinear analysis is shown in Figure 3.

5 RESULTS AND DISCUSSIONS

A typical example demonstrates the implementation in a beam subjected to zone II seismic loads as given in Section 1613 of international building code, 2018. Figure 4 and Figure 5 gives the load-deflection curves for different concrete and composites with cracks subjected to linear and nonlinear analysis.

It may be seen that initial stiffness (K1) and final stiffness (K2) vary in different ways for different composites. Here K1 is the normalized stiffness with reference to uncracked specimen with load taken at yield and K2 is the normalized value at a load causing a strain of .0035 or failure. Here in this paper the material property -Youngs modulus is normalized with respect to M30 grade of concrete. Ec is the Young's modulus of concrete of compressive strength 30 N/mm^2 Ecc is the Young's modulus of model or specimen. When Ecc/Ec equals to 1 then it is uncracked model, if Ecc/Ec is less than 1, then it is damaged model and Ecc/Ec is greater than 1 then it is the material property of concrete rehabilitated with composite. The stress contour obtained for a typical case is shown in Figure 6.

6 DESIGN RECOMMENDATIONS

Four cases have been considered to predict the type of composites to be used for rehabilitation. Here the composites to be used for rehabilitation is in the form of fibers, graded silica fume (Chen, 1995; Ghasson and Gregory, 2002; Binusukumar, 2006; Bharatkumar, 2007) and the modulus of elasticity is normalized with respect to concrete of grade 30.

The stiffness of the system is reduced, or in other words the displacement is increased under the following case

1. Crack width remains constant but crack depth (opening) increases at constant load.
2. Crack depth (opening) remains constant, but the crack width increases at constant load.
3. Crack width and depth (opening) remains constant but load increases.

4. Crack width, depth and load remain constant, but the material damaged.
5. A combination of two or more cases mentioned above.

6.1 Rehabilitation Measure

The composite chosen, for rehabilitation is based on two criterions.

1. Based on Stiffness: Initially there will be stiffness K1 and due to damage, it reduced to K2. The composite chosen, has to bring back the reduced stiffness (K2) to initial stiffness (K1)
2. Based on displacement: The displacement corresponding to K1 and K2 is designated as D1and D2. The displacement D, after the application of composite should be less than D1 and D2.

A typical case has been explained to predict the type of rehabilitation measure to be carried out for any damaged specimen. Assuming load, material property and crack opening remains constant but crack width increases from 0.1 to 0.2. Thereby the stiffness reduces by 52.57% and displacement increased by 10.52%. it is rehabilitated with the composite of Ecc/Ec=1.2, it added a stiffness of 38.37%, but the stiffness lost due to damages is 52.57% , therefore it is recommended to go for a composite which has higher Ecc/Ec value and is found that composite with Ecc/Ec=1.5 gave an additional stiffness of 80% and hence it is recommended for rehabilitation.

Dynamic responses for a specific cracked and damaged specimen before and after rehabilitation are shown in Figure 7 for linear and Figure 8 for nonlinear response . Here deflection responses are shown for both linear and nonlinear stiffness. The solution is done through numerical means to identify the shift in frequency, time period and changes in peak responses. With these results as templates, type and quantity of composites are identified for rehabilitation and an assessment of dynamic amplification factor is made.

Dynamic response of the system before and after rehabilitation under impulse load for different levels of damage/ crack has been found is compared with the uncracked section. Here the response of the system before rehabilitation refers to the response of the beam with damage or crack and similarly response of the system after rehabilitation refers to the response of the beam after the application of composite.

The width of the crack and load remains constant. Assuming there is no damage, but crack depth ratio increases from 0.1 to 0.2. The dynamic response of the system is shown in Figure 7. Composite provided is Ecc/Ec=1.2.All the cracking parameters remain same, but the load increases and if it exceeds the cracking load, the stiffness too get reduced and the dynamic response of the system is shown in Figure 8 and the composite provided for this case is Ecc/Ec=2. From the dynamic analysis, it is observed that as depth of the crack increases, it requires composite whose modulus of elasticity is lower than the composite required for material damages.

7. VALIDATION OF THE RESULT

Ghasson and Gregory (2002) rehabilitated the damaged concrete structures using carbon fibers is compared with the analytical study developed in this paper and is reported in Figure 9. The percentage increase in load after rehabilitation has been found to be 53% before yield displacement and 70% after yield displacement obtained from experimental investigation and is found to be 62% and 53% from analytical investigation.

Though the analytical results seem to be lie on the safer side, the variation is due to the uncertain parameters involved in analysis, particularly, the stress- strain values of the composite, the location, intensity and spread of the damages. In analytical investigation the grade of concrete assumed to be M30 (30 Mpa) , whereas in experimental investigation the concrete used is M45 (45 Mpa).

8 CONCLUSIONS

An attempt is made in this paper to study the dynamic linear and nonlinear behavior of concrete specimen. Three different parameters such as material property, width and depth of the crack are considered and their effect on displacement and stiffness of the models are studied. Based on the study on different models, design of composite is suggested for the rehabilitation of damaged beams. This study is validated with the experimental research and this research can be extended further for different seismic zones.

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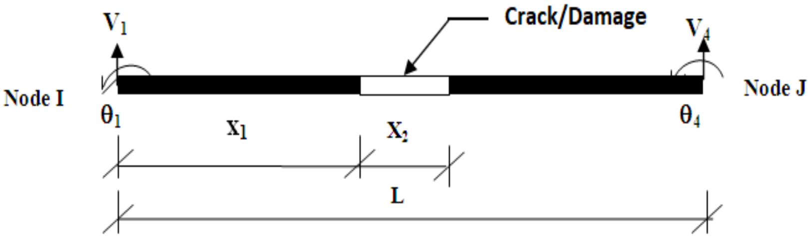


Figure 1 Concrete Beam with a Tensile Crack at the center

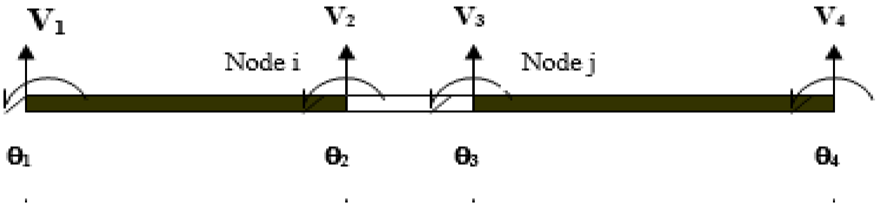
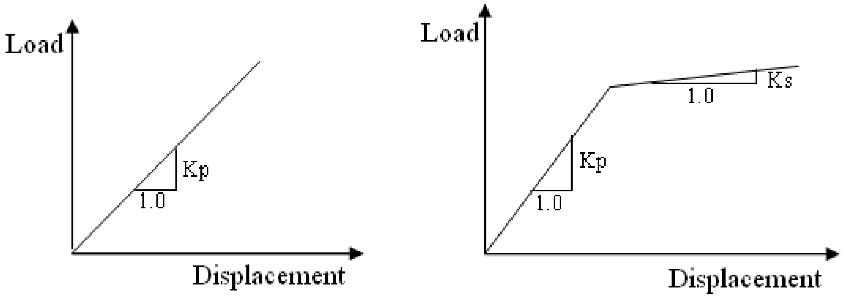


Figure 2 Beam Element into Three Sub-Beam Element with degrees of freedom



(a) Linear Analysis (b) Non-Linear Analysis

Figure 3 Modeling of Load Deflection Curve obtained from Static Analysis

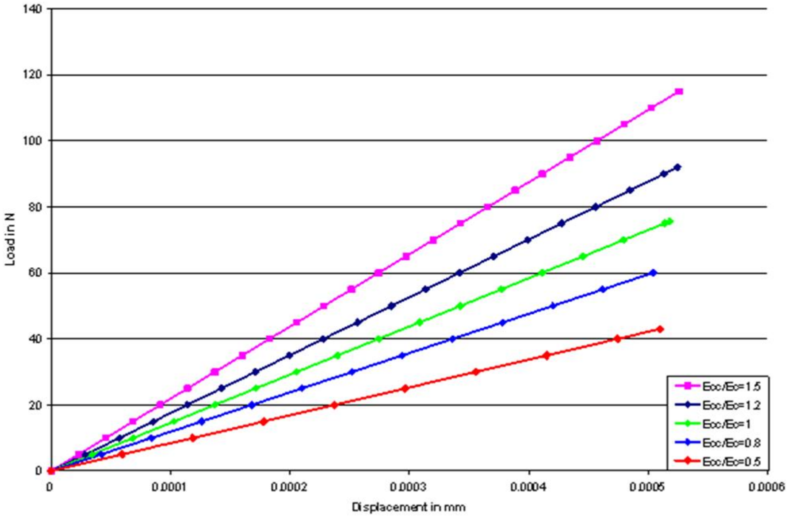


Figure.4 Load deflection responses obtained from linear analysis - crack depth/width ratio = 0.001/0.1

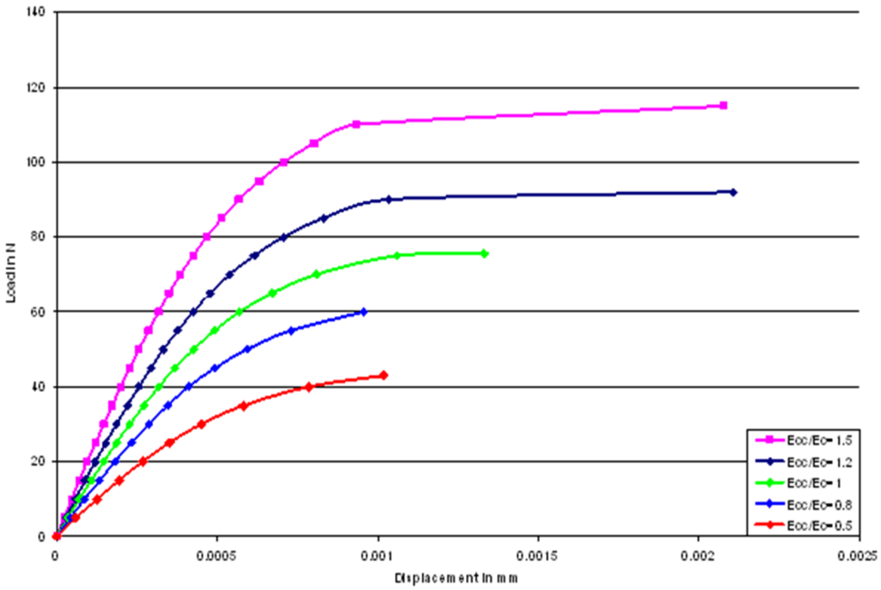


Figure 5 Load deflection responses obtained from non-linear analysis - crack depth/width ratio = 0.001/0.1

Table 1 Stress strain value of uncracked, cracked section before and after rehabilitation

Stage	**Before Rehabilitation**		**Uncracked section**		**After Rehabilitation**	
	Stress (N/mm^2)	Strain x 10^{-4}	Stress (N/mm^2)	Strain x 10^{-4}	Stress (N/mm^2)	Strain x 10^{-4}
Initial	0	0	0	0	0	0
Yielding	3.131	1.4	3.834	1.4	4.6	1.4
Ultimate	3.155	2.4	3.863	2.4	4.6874	4.06

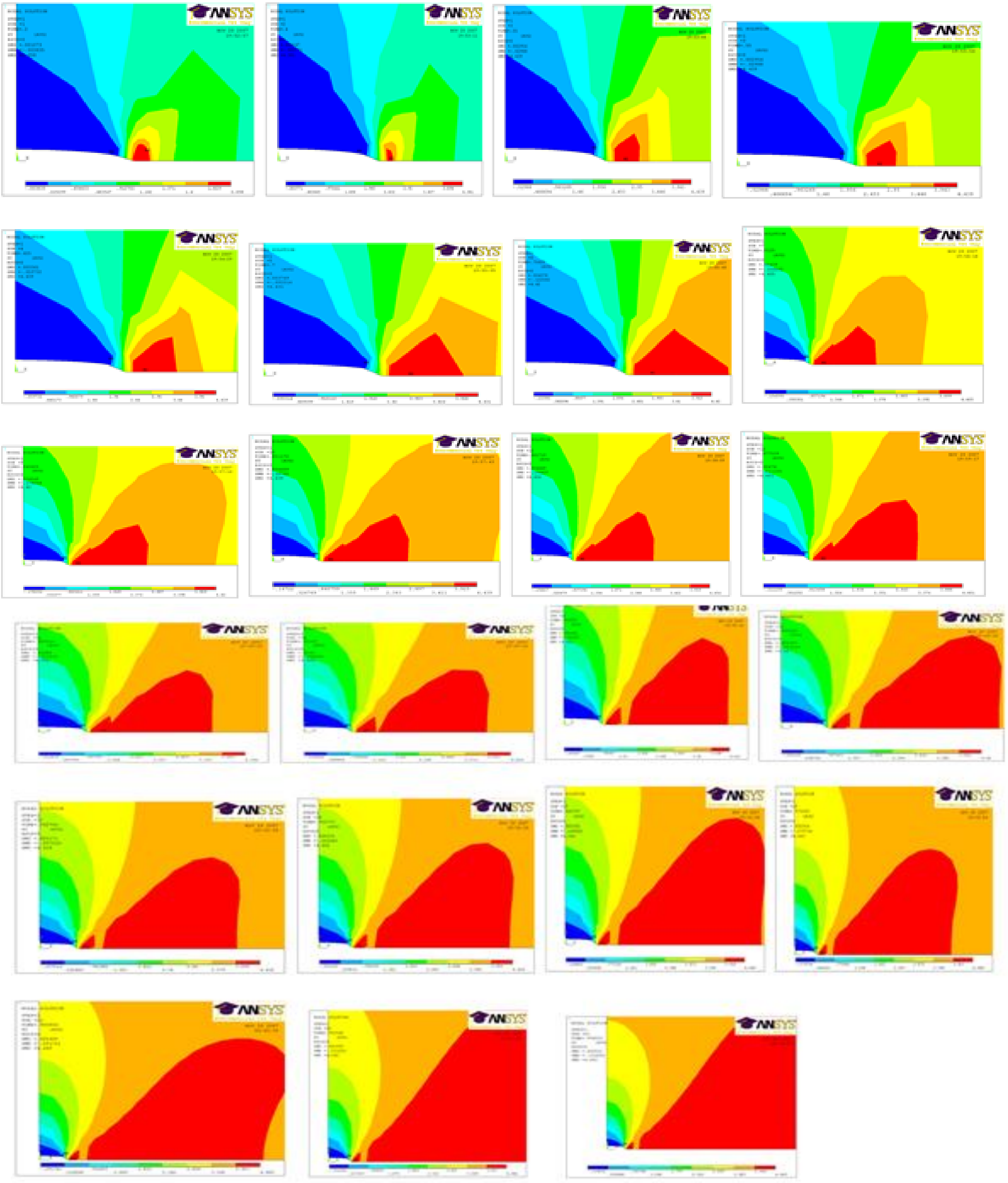


Figure 6 Stress Contours in Y direction for a typical failure cracking pattern

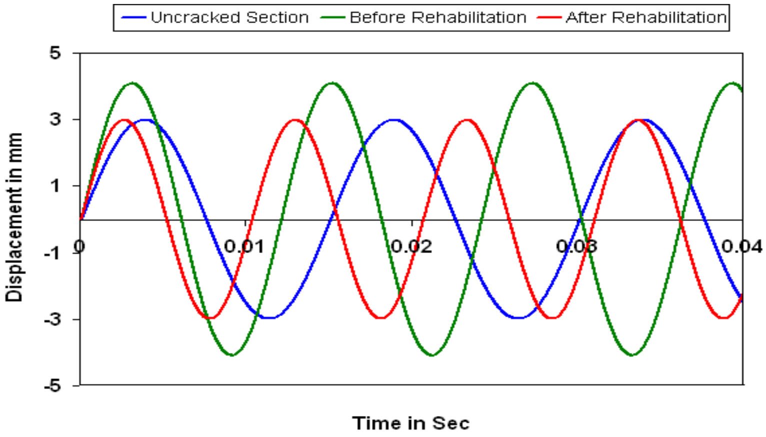


Figure 7 Linear Dynamic Response of the System before and after rehabilitation

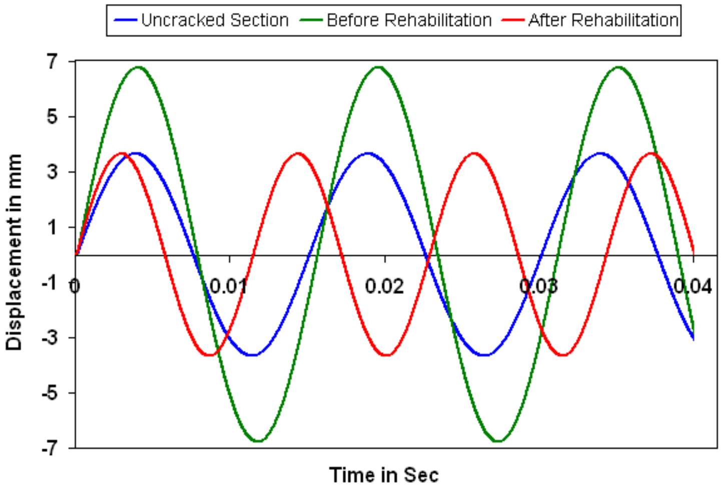


Figure 8 Non-Linear Dynamic Response of the System before and after rehabilitation

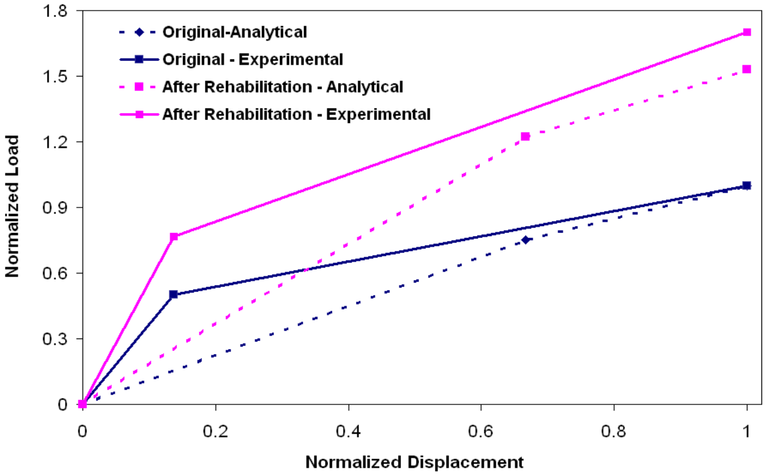


Figure 9 Normalized load displacement plot obtained analytically and experimentally where the displacement kept constant