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# ANALYSIS OF A CRACKED REINFORCED CONCRETE BEAM UNDER BENDING, AND REPAIRED WITH COMPOSITE MATERIALS

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### Abstract

During the process of the shear and bending failure of reinforced concrete beams, different cracks are generated on the side of the beam. Considering the material nonlinearity and geometric irregularity of reinforced concrete, and using concrete damage plasticity method, it is of great significance to study the dynamic evolution law of crack propagation in reinforced concrete members. Crack propagation consists of the elongation of the crack length at the surface of the concrete material. In this paper, a finite element model of a reinforced concrete beam subjected to flexure load is established by considering the damage of the concrete, and then comparing the fracture parameters values such as Stress intensity factor and Von Misses stress, with the valued obtained after applying a composite patch material to repair the reinforced concrete beam, the finite element model can accurately reflect the behavior of the structure with the presence of the cracks and then with the repair method, The concrete damage plasticity is applied to the numerical model as a distributed plasticity over the whole geometry. The objective of this study is to predict failure and crack development in the concrete model using finite element method code compute ABAQUS for static load. [1]

**Keywords:** Reinforced Beam; Concrete damaged plasticity; Stress intensity factor; Composite materials.

## 1. INTRODUCTION

The field of fracture mechanics studies how cracks form in materials when loads are applied in all directions. When there is more excess tensile stress than tensile strength, brittle fracture material cracks. If the applied load is greater than the fracture resistance and toughness of brittle solids like plain concrete, it will cause the cracks to form faster and eventually lead to the failure of the individual structural elements or the entire structure. Thus, the mechanism of elastic stress distributions surrounding cracks and their development can be better understood with the aid of linear elastic fracture mechanics; Yuqing Yang, and al used numerical simulation in the study of such problems [2]. Based on the energy-based theory of failure, fracture mechanics was pioneered by Griffith [3].Namdar, A., and al. has conducted an experimental investigation into the flexural crack on a plain concrete beam as. [4]. Dhondt, G.**,** and al; numerically simulated the state-of-the-art, prediction of three dimensional crack propagation paths to observe the damage [5].

Reinforced concrete (RC) is a crucial building material that is extensively utilized in various engineering structures. Its economic advantages, strength, and stiffness make it a popular choice for a wide array of structural applications. In order to create efficient and safe structures, it is important to understand how structural components respond to loading. Various methods have been employed to analyze the behavior of these components. The theoretical computations that estimate deflections at the serviceability load of the beams are compared with the obtained results. Additionally, finite element analysis can be used to numerically model the behavior to validate these calculations and serve as a useful addition to lab investigations, especially in parametric studies. With the continuous development of finite element theory and computer technology, the development of finite element analysis software is maturing.

ABAQUS, as one of the largest universal finite element analysis software, is increasingly commonly used in research works and engineering. Because not only does it have high speed, high accuracy, and low-cost analysis of the numerical calculation of finite element analysis software, but also has a more user-friendly operator interface and visualization results, especially when it is used in the nonlinear analysis of reinforced concrete structure LIU, J. S., and al [6]**.** Tejaswini, T., and al compared the numerical results from the FEA from ABAQUS with the experimental results which showed good agreement between the results. Laboratory tests were carried out for plain, under, balanced, over reinforced sections.

The failure mechanism of a reinforced concrete RC beam was modeled quite well using FEA and the failure load predicted was very close to the failure load measured during experimental testing. [7]. Buckhouse, E. R. work on Simply supported RC beam analysis with the plasticity model of concrete damage in ABAQUS when compared with the experimental result revealed that FEM analysis result was found similar to numerical analysis so can be a reference for the further study of the nonlinear analysis of reinforced concrete [8]. By considering the impact of compressive strain localization, a model was created.

Various methods for applying fracture mechanics to concrete are explored, with a focus on models that rely on strain localization and softening, especially the fictitious crack model. [9]. A fracture mechanics model for bending of RCC beams where concrete is assumed to be a linear elastic material and steel is considered to be elastic- plastic was proposed. The effect of reinforced steel bars is simulated by a closing force whose magnitude is determined by a compatibility condition [10]. Bosco, C., studied a fracture mechanics approach to predict cracking of RC members subjected to tension by balancing the rates of change of the strain energy, the debonding energy, and the sliding energy was developed [11].

## 2. MODEL AND FRACTURE PARAMETERS

### 2.1. Concrete damaged plasticity

The Concrete Damage Plasticity (CDP) is the most comprehensive continuum model that was used in the reinforced concrete beam simulation to define concrete behavior in this analysis. The CDP model applies to concrete that is subjected to monotonic loading for different types of structures (such as beams, trusses, shells, and solids) and it is developed based on two concrete failure mechanisms. a) Compressive crushing b) Tensile cracking. For concrete subjected to uniaxial loading, the stress-strain response of concrete in tension exhibits a linear elastic relationship until the failure stress is achieved, and beyond that point, the concrete follows the softening stress-strain behavior. When the concrete is unloaded at any point from within the strain- softening portion of the curve, the unloading response is weakened and the elastic stiffness of concrete is damaged. This deterioration of the stiffness is defined by the damage parameter in tension ($d_t$), which can range from zero representing the undamaged condition of the specimen to one which signifies that the material has lost its total strength.

The concrete damage plasticity (CDP) model in Abaqus is used to create the constitutive model for pre-fabricated slab. The CDP model is commonly used to represent the behavior of quasi-brittle materials such as concrete, rock, and masonry. It is based on the basic concept presented by [17] and the improvements proposed by [Lee and Fenves, 1998]. In the sense that it does not monitor individual macro fractures, the concrete damage plasticity model in ABAQUS is a smeared crack model.

The finite element constitutive model's calculations are done separately at each integration point, and the existence of cracks enters the calculations by changing the stress and material stiffness associated with the integration point. This model suggests that the behavior of concrete under uniaxial compression and tension is governed by damaged plasticity, with compressive crushing and tensile cracking as the primary failure modes. The stress-strain relationship in uniaxial tension is considered to be linear until the failure stress, σt0, which corresponds to the beginning of macro-cracking, is reached.

This is frequently followed by softening, which results in strain localization. In uniaxial compression, it is also presumed that the reaction is linear until the first yield stress, σc0, after which a plastic regime, often characterized by strain hardening to the ultimate stress, cu, and then softening, takes over. CDP is premised on the idea that uniaxial stress-strain relations can be automatically converted into stress-equivalent plastic strain curves using user-supplied inelastic strain data. The present condition of the yield surface, which is utilized to assess multiaxial load scenarios, is then determined by computing the effective tensile and compressive cohesion stresses.[12]

### 2.2. Cohesive zone model

Crack zones can be modeled either with methods such as Linear Elastic Fracture Mechanics (LEFM), Crack Tip Opening Displacement (CTOD) or a more recently Cohesive zone method (CZM). The Cohesive zone model is the most important evolution in the area of Fracture mechanics. It is widely used to simulate crack initiation and its propagation in solids. It is also an alternative method for model separation. For CZM fracture formation is regarded as a gradual phenomenon in which the separation of the surfaces involved in the crack takes place across an extended crack tip, or cohesive zone, and is resisted by cohesive traction. Thus cohesive zone elements do not represent any physical material but describe the cohesive forces which occur when material elements (such as grains) are pulled apart, therefore cohesive zone elements are placed between continuum (bulk) elements [13].

In our work we analyses the behavior of a Steel reinforced concrete beam under bending loads, throughout the study of plastic, and fracture parameters such as Von Mises stress Displacement and Stress intensity factor, using Finite Element method implemented in the code compute Abaqus, for different loads, crack sizes, and with a Composite material Patch used to repair the cracked beam.

## 2.3. Von Mises stress

An engineer's duty is to keep the maximum value of von mises stress induced in the material less than its strength, and Von Mises stress theory, which can be expressed in the formula $N = \sigma_y / \sigma'$, is suitable for computing the safety factor against failure. It is a theoretical measure of stress used to estimate yield failure criteria in ductile materials and is also popular in fatigue strength calculations (where it is signed positive or negative according to the dominant Principal stress), whilst Principal stress is a more "real" and directly measurable stress.

## 2.4. Stress Intensity Factor (SIF)

The stress intensity factor (SIF) measure predicts the stress state near a crack tip or crack front caused by a load or residual stress. You can create a SIF measure after defining a crack idealization. SIF value can be evaluated in a static analysis to predict the growth of a crack under specific loading conditions. In case the mesh near the tip of the crack is too coarse you can refine it using the configuration option Sim-SIF measure size factor, SIF measures are calculated for static analyses with small deformations and for models with linear elastic materials only.

### 2.4.1. Computation of the SIF

The SIF for a varying crack length is achieved by interpolation of computed $\Delta K$ for several specific crack lengths. In 10 relation to static simulation, a clear increase in the computed $\Delta K$ was shown when using a dynamic simulation including the frequency and damping effect.

For elastic–plastic materials with non-linear material deformation in a large region around the crack tip, the linear elastic fracture mechanics (LEFM) is no longer valid. However, the plastic deformation is taken into account in the elastic–plastic fracture mechanics (EPFM) model2 where the crack tip conditions are described by the J-integral or the CTOD parameters. The experimental testing at 20 kHz with the ultrasonic fatigue system is a displacement controlled testing procedure run according to Equation (). The displacement of the top surface of the specimen U0 is the controlled amplitude during testing.3

$$K_I = \frac{E_d}{1-v^2} U_0 \sqrt{\frac{\pi}{a}} f \frac{a}{w}, \tag{1}$$

Where $E_d$ and $v$ are the dynamic elastic *Young's modulus* and *Poisson's ratio*, respectively. A is the crack length and the function f(a/w) is the dimensionless shape function to be calibrated, from Equation (1) it is seen that the effects of U0, Ed and v on the SIF are simple and clear. However, there are more material properties involved in this computation, for example, density and damping. These two properties used in the simulations calibrating the shape function *f (a/w)* and are hence embedded in it.

The Rayleigh damping model, Equation (1), is implemented in the FEM software Abaqus and was conveniently used in all simulations.18

$$\xi = \frac{\alpha_R}{2\omega} + \frac{\beta_R \omega}{2}, \tag{2}$$

Where ω is the angular frequency and αR and βR are the mass- and stiffness proportional damping coefficients, respectively. At high frequencies (e.g., 20 kHz), the effect of the mass proportional damping is insignificant, and the stiffness proportional damping becomes the dominant part of the Rayleigh damping, as seen in Equation (2).

## 3. MODEL AND GEOMETRY

Our model consists of a concrete beam reinforced with Steel, and contains a crack. The simply supported beam is 3000 mm long with an effective length of 200 mm and a cross-section of 300 mm width, the beam is subjected to bending load. Longitudinal reinforcement with a yield stress of 500 N/mm$^2$ (Fe500) and confinement bars with a yield stress of 415 N/mm$^2$ (Fe415) was used. The density of steel 7.5x10$^{-5}$ N/mm$^3$, young's modulus 200000 N/mm$^{2,}$ and Poisson's ratio 0.3 are used (Figure 1).

**Fig 1: Beam geometry [14]**

**Table 1: Material Properties**

| | E Young modulus (GPa) | M (Poisson ratio) |
|---|---|---|
| Concrete Beam | 30 | 0.18 |
| Adhesive Plate | 2 | 0.35 |

**Table 2: Composite Patch Properties**.

| Patch properties | E1 (GPa) | E2 (GPa) | G (GPa) | μ |
|---|---|---|---|---|
| (T 300/934 ) | 148 | 9.65 | 4.55 | 0.33 |

## 4. FINITE ELEMENT MODELING

In Abaqus, three-dimensional solid C3D8R elements are used for concrete and two-node three-dimensional linear truss T3D2 elements are used for reinforcement. Rigid pads are used to transfer the concentrated forces and the pads are C3D8R elements. The reinforcement cage is embedded in the concrete.

To get accuracy in results, all the elements of the FE model were assigned the same mesh size so that every two different materials can share the same node among them. After assembling and assigning the properties, an input file is created which is then imported to create a mesh. The elements used for the study are C3D8R (8-node linear brick) and T3D2 (2- node linear 3-D truss.

The concrete beam is modelled in 3-D assigned with C3C8R elements and reinforcement in the longitudinal direction, and the shear reinforcement bar is modelled in 2-D was assigned with the T3D2 element. Meshing was adopted for all of the elements used in the models. Also, the aspect ratios of solid elements were kept as close to one as practicable, as high aspect ratio elements would affect the accuracy of the analysis. [16].

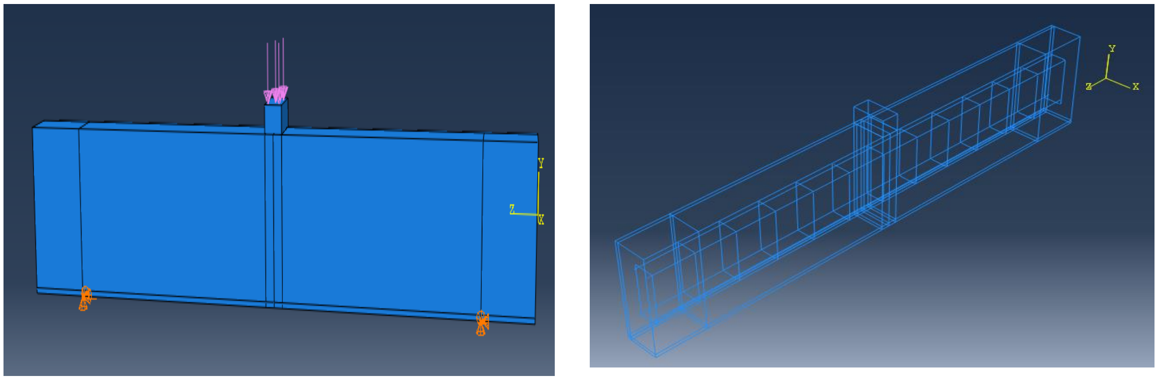

**Fig 2: Steel bars modeling with Abaqus [15]**

## 5. RESULTS AND DISCUSSION

### 5.1 Von Mises Stress Results

The following figures represent Stress Intensity Stress in the case of unrepaired crack of 10mm length, and 40mm Width (Fig.3), crack length of 50mm, and 40mm Width (Fig.4.), Unrepaired and unrepaired beam (55 MPa) in (Fig.4, and Fig.6)

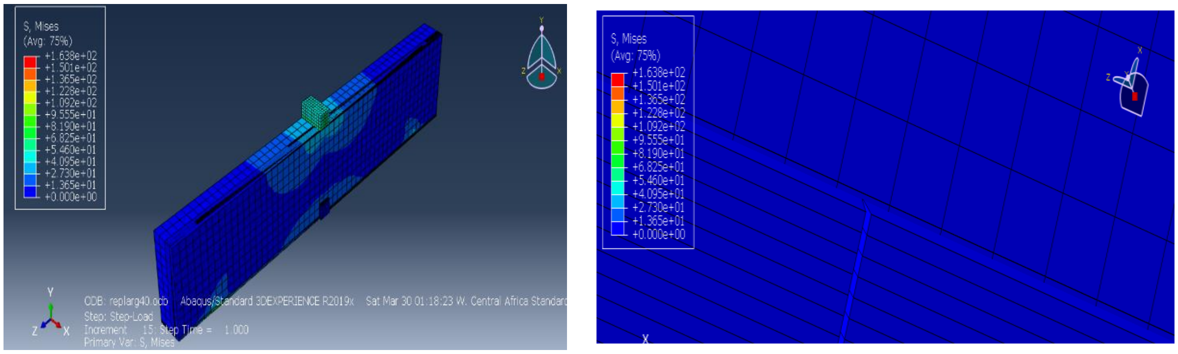

Fig 3: Von Mises stress for an unrepaired crack of 10mm length, and 40mm Width

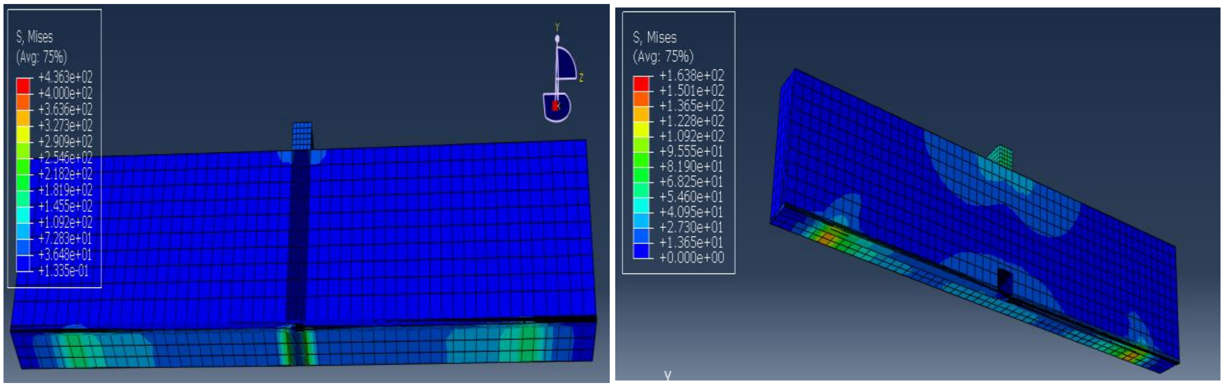

Fig 4: Von Mises stress for a crack length of 50mm, and 40mm Width

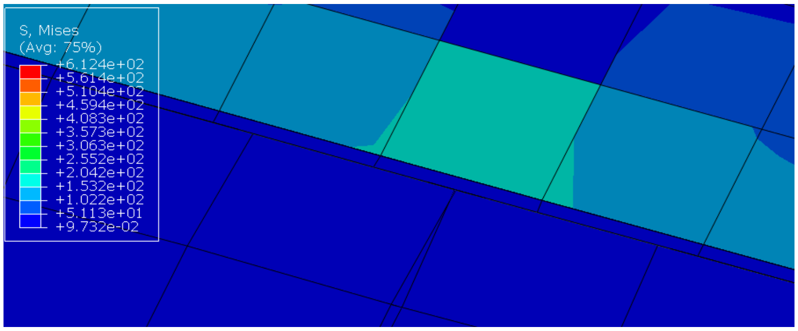

Fig 5: Von Mises Stress for an Unrepaired beam (55 MPa)

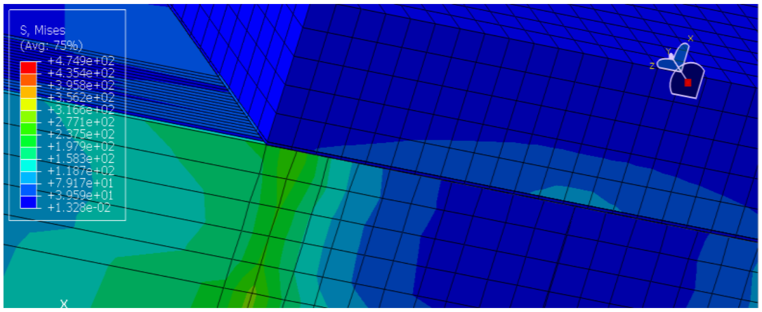

Fig 6: Repaired beam for a repaired beam

The results show the intensity of Von Mises Stress for each case, we can notice that:

- The intensity of the stresses around the crack head and the crack opening is clearly noticeable in the unrepaired beam.
- It can be seen that, the values are high, for the unrepaired reinforced concrete beam as the crack size increases for the repaired beam; however, the values are much lower, confirming the effectiveness of the composite patch in repairing cracks.

### 5.2 Stress Intensity Factor Results

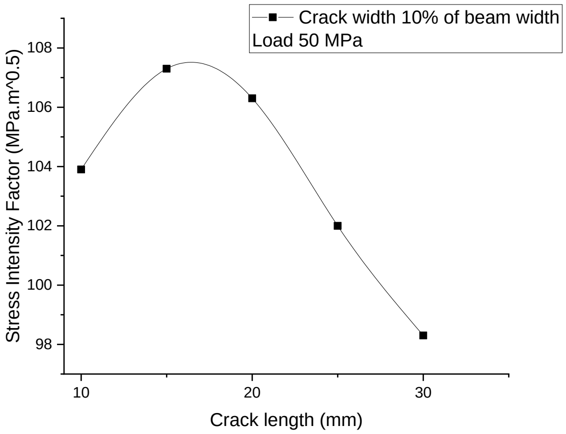

**Fig 7: Stress Intensity Factor in function of Crack length (crack width 10%) for unrepaired reinforced concrete beam**

Figure 7 represents the variation of Stress Intensity Factor in function of Crack length, SIF values start to increase from 103.9(MPa.m$^{0.5}$) at crack length equal to 10mm, to 107.3(MPa.m$^{0.5}$) at crack length equal to 15mm, and then it start gradually increasing until it reach 98.3(MPa.m$^{0.5}$) at crack length to 30mm, SIF values decrease rapidly from 106(MPa.m$^{0.5}$), at a crack length 20mm to 84.41(MPa.m$^{0.5}$) at crack length 70mm.

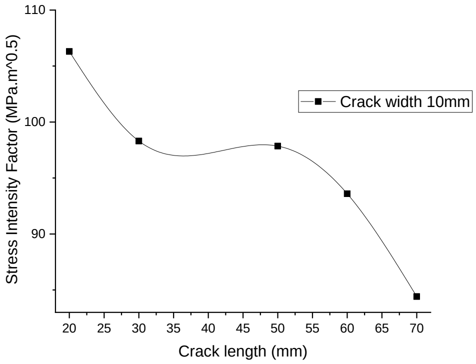

**Fig 8: Stress Intensity Factor in function of Crack length (Crack width 10mm) for unrepaired reinforced concrete beam**

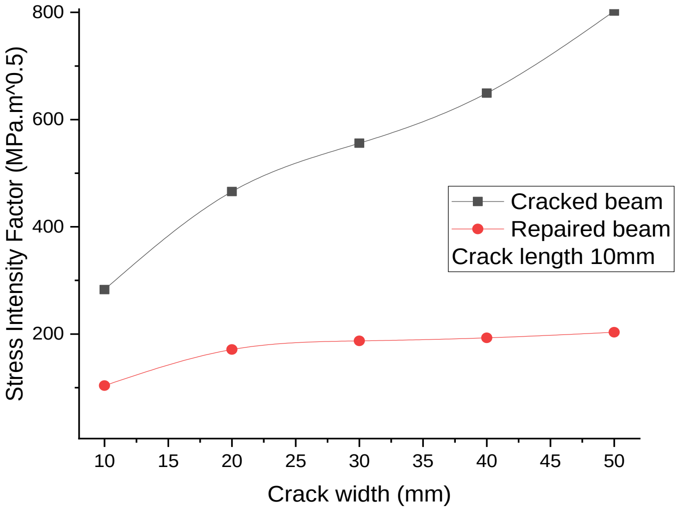

**Fig 9: Stress Intensity Factor in function of Crack width (Crack length 10mm) for both repaired and unrepaired reinforced concrete beam.**

The figure above shows SIF values differences for both repaired and unrepaired reinforced beam, while SIF values are highly increasing for the unrepaired beam (reaching up to 802.3(MPa.m$^{0.5}$) which is almost 3 times the initial value), SIF values are almost constant for the repaired beam and the final SIF value 203.4(MPa.m$^{0.5}$) is only 2 times the initial value. We can notice that SIF values are much lower for the repaired beam (the difference is almost 40%).

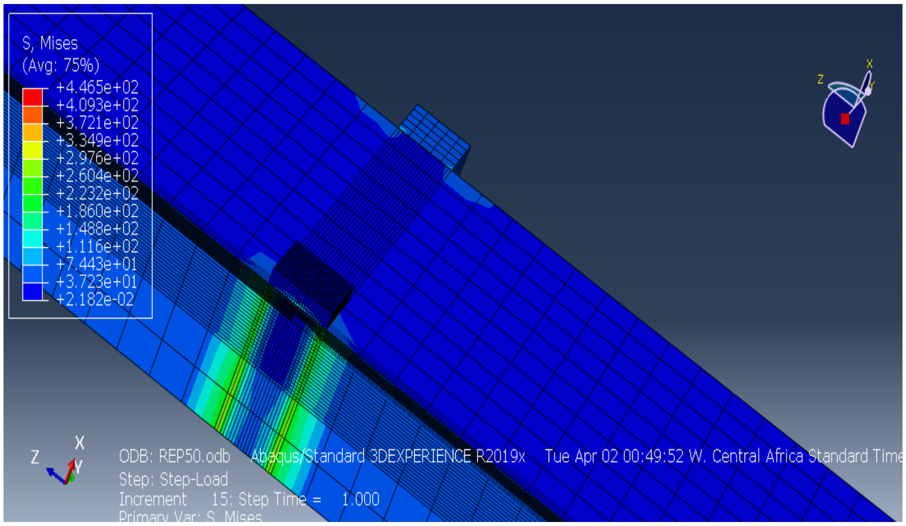

**Fig 10: Repaired beam with composite patch with a crack dimension (30X30) mm**

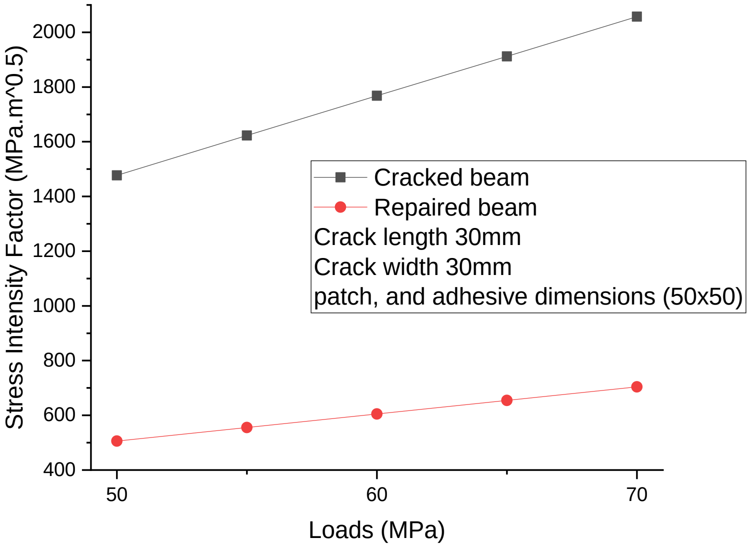

**Fig 11: Stress Intensity Factor in function of Bending Loads, for both repaired and unrepaired reinforced concrete beam.**

Figure 11 represents the Stress Intensity Factor variation in function of Bending Loads, with Crack dimension (30x30)mm for both repaired and unrepaired reinforced concrete beam, it is clear that the difference between the two curves is quite remarkable.

The diminution of SIF values in the case of reinforced concrete (RC) beams that have been strengthened using carbon fiber reinforced polymer (CFRP) is about 66%, which proves the efficiency of this method of repair for this crack dimensions

## 6. CONCLUSION

The analysis of the fracture parameters variations, allowed us to understand the behavior of the reinforced concrete beam with the presence of cracks with different sizes, and under different bending loads values, it can be concluded that the crack size highly affects the variation of both, Von Mises Stress values, and the Stress Intensity Factor value, and the use of composite repaired method on the cracked area has attenuated this values, which allows the structure to be more resistant and stable.

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