Rehabilitation of Corroded and Cracked Steel Beam Using Hybrid Laminates with Post Tensioning

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Abstract *- The steel beams with crack and corrosion can result in the reduction of stiffness, load carrying capacity and hence it results in the worst performance of the beam. Flexural rehabilitation of corroded steel beams using Carbon Fibre Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) have been studied in the past. However, studies have not been conducted on the rehabilitation of corroded steel beams using hybrid laminates along with post tensioning . This study examined the feasibility and effectiveness of using hybrid laminates made with combining CFRP, BFRP and GFRP for rehabilitation of corroded and cracked steel beams. The steel beams examined are of with 10% ,20%, 40%, 50% and 75% corrosion and precrack at flexural and shear zone. These steel beam models compared with control beam model that is, steel beam having no crack and corrosion. Among these models, worst model were rehabilitated using hybrid laminates and post tensioning. Comparison of model retrofitted using CFRP, GFRP and BFRP with model retrofitted with hybrid laminates were also examined. Non linear finite element models were developed by using ANSYS to assess structural performance of these beams. Three point bending tests were used to analyse the beams with and without rehabilitation.*

Key Words: Rehabilitation, Hybrid laminates, Post tensioning, Precrack, Finite element analysis

1. INTRODUCTION

Many bridges, parking garages, and other structures in the world are in need of rehabilitation or replacement. For reinforced concrete and steel bridges and parking garages, corrosion is one of the main causes of deterioration. Various methods are available for rehabilitating corroded steel beams. The most common method of corrosion repair includes either welding or bolting steel plates after the beam has been cleaned of the corrosive products. However, this procedure is labour intensive and time consuming. Further, this procedure introduces the potential for weld cracking failure at the ends of the steel plates when the welding method is used in the rehabilitation. Regions of high stress concentrations could develop near bolts when the bolting method is used.

Fiber Reinforced Polymer (FRP) fabrics are composite materials containing an epoxy matrix reinforced with fibers. Common types of FRP fabrics used are Carbon FRP (CFRP), Glass FRP (GFRP), and Aramid FRP (AFRP). Due to its high strength-to-weight ratio and cost effectiveness, the use of FRP fabrics has been useful and is gaining popularity in the rehabilitation of structures. FRP fabrics may be slightly more expensive than steel plates. However, since welding or bolting is not required, the cost of labour is much lower.

Earlier studies found that the rehabilitation of corroded and cracked steel beams using CFRP fabric resulted in a moderate increase in the elastic stiffness and significant increase in the ultimate strength. It is also found that an improvement in the flexural moment capacity of steel structures strengthened with CFRP. Studies also found that steel beams strengthened using GFRP fabric resulted in increased elastic stiffness, and yield and ultimate moment capacities. However, the ductility of beams rehabilitated using CFRP or GFRP fabrics decreased and this occurs due to the brittle failure mode of FRPs.

A concerning issue with the use of CFRP for steel rehabilitation is the increased possibility of galvanic corrosion. The cause for galvanic corrosion is the electrochemical coupling of two dissimilar metals, which creates an electric current. CFRP and steel are dissimilar metals, hence direct contact between steel and CFRP needs to be avoided. Therefore, the use of an E-glass layer was recommended to electrically insulate CFRP and steel. Galvanic corrosion is not a concern at all for Basalt FRP (BFRP) as it is not a conductor, and thus, it does not require any electrical insulation. Basalt fiber is made from basalt rock through a melting process. In the manufacturing process, it contains no additives so the product is nontoxic and recyclable. Hence, basalt products are a greener option as compare to both carbon and glass fiber fabrics. Further, basalt fibre fabric's cost is about 1/5th of carbon fiber fabric . On comparing the performance of concrete beam rehabilitated with CFRP, GFRP and BFRP, the performance of beam rehabilitated with BFRP fabric lies in between the performance of concrete beams rehabilitated with CFRP and GFRP fabrics also the concrete beams strengthened with BFRP fabric exhibited higher yield and ultimate load capacities as compare to GFRP. However, the ductility of the strengthened and rehabilitated concrete beams with BFRP fabric reduced when compared to that of the control specimens.

In addition to these methods, external prestressed tendons have been used to strengthen existing composite steel–concrete beam structures. This technique involves welding end anchorages and using conventional high-strength post-tensioning cables. Results proved that the initial force in the tendon and its eccentricity significantly affect the strength and stiffness of tested beams. Furthermore, this type of strengthening leads to a 25% increase in load carrying capacity in some cases. As an alternative to the above mentioned methods, applying prestressing in a localised region within a steel beam for strengthening existing steel bridges and repairing severely damaged steel I-beams. This method increases the stiffness and the load carrying capacity of the steel structural member through adding reinforcing steel bars to a segment of the beam. Prestress is achieved by elevating the steel bars from the soffit of the steel beam by using a manual screw jack that generates a tensile force in the steel bars. Due to the low cost and the ease of operation, this method is also used to prestress concrete beams.

2. FINITE ELEMENT MODELLING

2.1 General

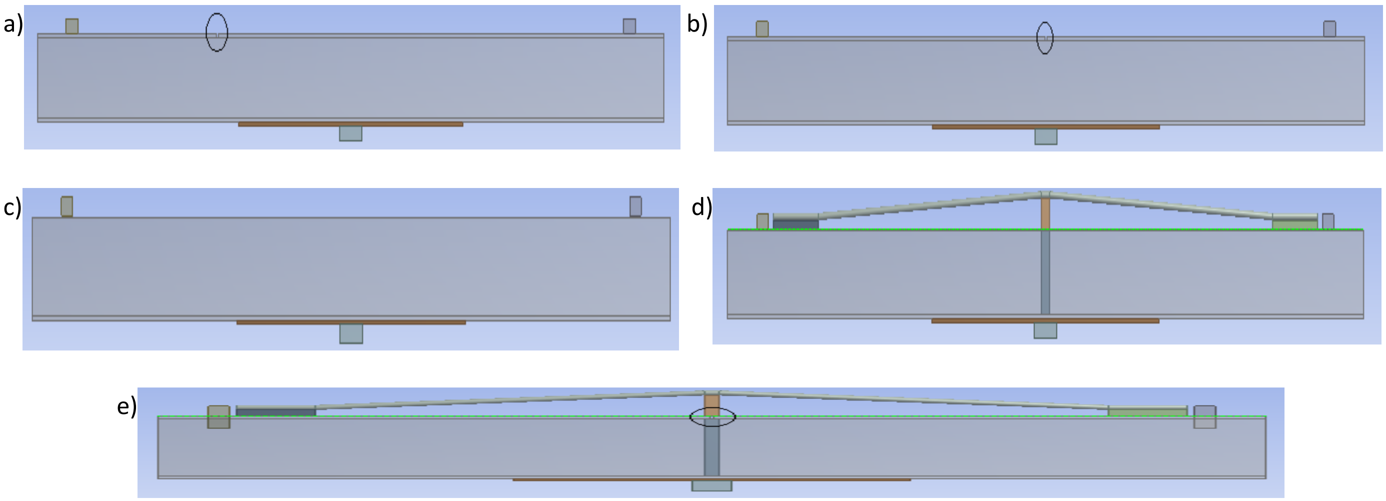
To rehabilitate the corroded and cracked steel beam using hybrid laminates with post tensioning, finite element models were developed using ANSYS 16.1. Solid186 elements were used to model square and circular steel tubes. SOLID186 is a higher order 3D 20-node solid element that exhibits quadratic displacement behavior. The element is defined by 20 nodes having six degrees of freedom per node; translations and rotations in x, y and z-directions.

2.2 Scope

The work is limited to modelling and analysis of steel beam corroded at different levels and having precrack, also rehabilitation of it with CFRP, GFRP, BFRP and hybrid laminates with post tensioning by using ANSYS. The investigations are carried out to study the flexural rehabilitation of defected steel beam using Non linear finite element approach. Strengthening of the corroded and cracked steel beam using hybrid laminates and rehabilitation of the same with post tensioning method can be analysed to restore the stiffness and ultimate load carrying capacity. The study includes the behaviour of seven models in which the five of them are corroded at different levels like 10%, 20%, 40%, 50% and 75% and the other two are pre cracked. The study also includes the rehabilitation of these models and optimizing the moment capacity and stiffness, hence reduce further damage to the structure using cost effective laminates and post tensioning methods.

2.3 Geometry

Key geometric properties of the steel beam are an overall depth of 150 mm, a flange width of 75 mm, flange thickness of 7.0 mm and web thickness of 5.0 mm. The yield stress, the ultimate tensile strength and Young's modulus were 411.6 MPa, 541.3 MPa and 207.4 GPa respectively, obtained through tensile coupon tests. The width of the crack at the flexural zone and shear zone is 5mm is provided. The geometry of steel beam with crack at flexural zone is shown in the figure 5.1. The geometry of steel beam with crack at shear zone is shown in the figure 5.2. Multilinear isotropic hardening is used to reproduce plastic behavior of materials. In all above cases weight remain constant. Steel beam corroded at different levels that is 10% ,20%, 40% ,50% and 75% are by deducting its flange thickness. The thickness of single layer laminates (CFRP, BFRP, GFRP) used for rehabilitation is of 1mm and the multilayer hybrid laminate is composed of BFRP, CFRP and GFRP together with thickness 0.34mm, 0.13mm, 0.17mm respectively. Local prestress was applied using deformed reinforcing bars 500 N, typically used for reinforced concrete structures. The diameter of bars used for prestressing is 16mm. The material properties of steel, tendon and hybrid laminates are shown in Table 1. The geometry of the above mentioned steel beams are shown in Figure 1. Multi linear isotropic hardening is used to reproduce plastic behavior of materials.



a) Precrack at shear zone b) precrack at flexural zone c) 75% surface corrosion d) retrofitted with hybrid laminates and post tensioning(surface corrosion 75%) e) retrofitted with hybrid laminates and post tensioning (precrack at flexural zone)

Fig -1: Geometry of Steel beam with precrack (at shear zone, at flexural zone), at 75% of corrosion, retrofitted steel beam using hybrid laminates with post tensioning (surface corrosion 75%, precrack at flexural zone)

Table -1: Material Properties of Steel, Tendon, Hybrid Laminate(BFRP, CFRP, GFRP)

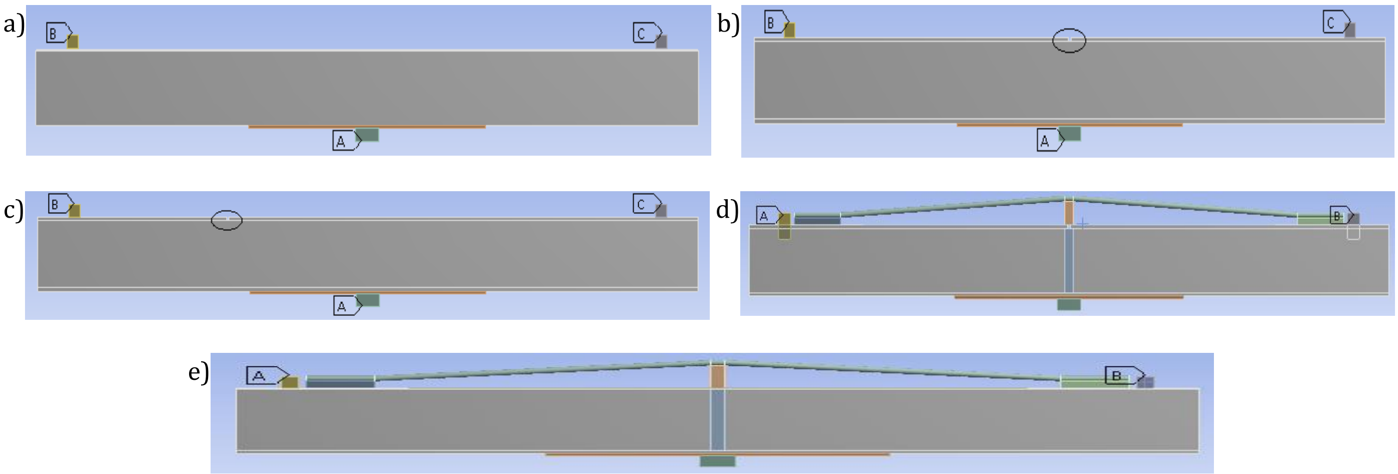
Material Properties	**Steel**	**Tendon**	**Hybrid Laminate**		
			BFRP	CFRP	GFRP
Young's Modulus (MPa)	2.07e+05	2.07e+05	108000	230000	71000
Tensile Strength(MPa)	541.3	541.3	3000	3500	2000
Yield Strength(MPa)	411.6	500	-	-	-

2.4 Meshing

Meshing divides the whole component into a finite number of small elements as per requirement. Size of the element must be as small as possible to achieve accuracy. In this analysis, fine mesh was adopted to achieve maximum accuracy in results. Solid models are converted into a finite element model after meshing. The selected three-dimensional model of steel beam was developed by finite elementsoftware to demonstrate the behavior properly.

2.5 Loading and Boundary conditions

Three-point bending tests were conducted in a universal testing machine with a loading capacity of 1000 kN. Each beam specimen was simply supported on two roller supports with a span of 1250 mm. The load was applied through a roller from above in the middle span of the beam. A 3D finite element model was formed for each beam and comparison was made each other. Boundary conditions of the steel beam having 75% surface corrosion, having precrack at flexural zone and shearzone, and these beams rehabilitated by hybrid laminates with post tensioning are shown in Figure 2.



a) 75% surface corrosion b) Precrack at flexural zone c) precrack at shear zone d)retrofitted with hybrid laminates and post tensioning(precrack at shear zone) e)retrofitted with hybrid laminates and post tensioning (surface corrosion 75%)

Fig -2: Geometry of Steel beam with precrack (at shear zone, at flexural zone), at 75% of corrosion, retrofitted steel beam using hybrid laminates with post tensioning (surface corrosion 75%, precrack at flexural zone)

3. ANALYTICAL RESULTS AND DISCUSSIONS

3.1 Steel Beam with Different Levels of Corrosion and Precrack

Beams with precrack (at flexural zone and shear zone) and corrosion at different levels(10%, 20%,40%, 50% and 75%) are subjected to load at the middle of the span. Chart 1 shows comparison of Load-Displacement curve of the above mentioned steel beams. Table 2 shows values of ultimate load and corresponding deformations of the above steel beams. Figure 3 shows total deformation.

Table -2: Comparison of ultimate load and deformations of steel beam with precrack and at different levels of corrosion

Steel Beam	Max Deformation (mm)	Ultimate load (kN)
No surface corrosion and precrack	12.627	169.15
Surface corrosion(10%)	12.626	160.05
Surface corrosion(20%)	12.630	150.76
Surface corrosion(40%)	14.919	131.12
Surface corrosion(50%)	14.922	121.51
Surface corrosion(75%)	14.929	97.16
Precrak at Flexural zone	13.348	88.982
Precrack at Shear Zone	13.283	144.53

From results, it is clear that the steel beam having surface corrosion 75% and the beam having precrack at flexural zone having more loss in the ultimate load as compared with the same with out surface corrosion and precrack. Displacement controlled force is given in finite element analysis. At the initial stage, all beams will be in an elastic state. When the ultimate load is reached, the steel beam fails.

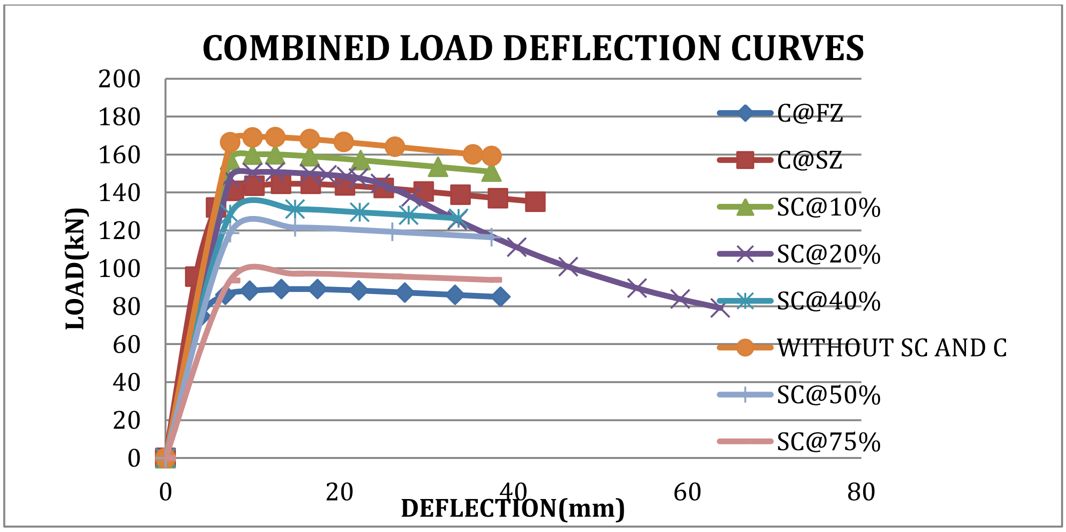
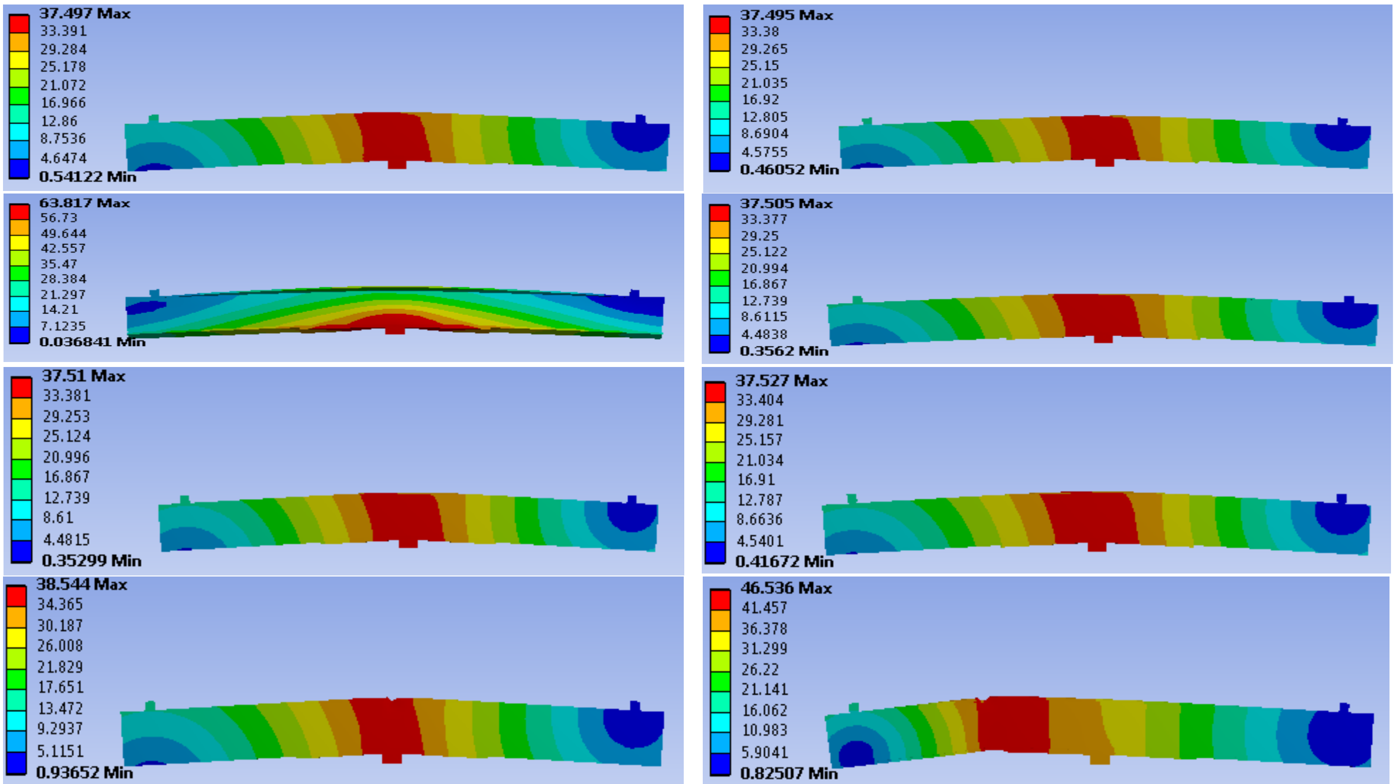


Chart -1: Comparison of Load – Displacement curves



a)no surface corrosion and pre crack b)surface corrosion 10% c)surface corrosion 20% d) surface corrosion 40% e) surface corrosion 50% f) surface corrosion 75% g) precrack at flexural zone h)precrack at shear zone

Fig -3: Total deformation of steel beam with precrack and corrosion

From this it is clear that the steel beam with precrack at flexural zone and surface corrosion of 75% gets fail first.

3.2 Different Methods of Retrofitting

Table 3: Comparison of different methods of retrofitting the beam with 75% surface corrosion

Methods of rehabilitation	Ultimate load	Max. deformation
Using BFRP	127.34	26.077
Using CFRP	111.75	14.871

Using GFRP	106.91	22.332
Using post tensiong	201.16	14.839
Using hybrid laminates	151.83	26.094
Using hybrid laminates with post tensiong	213.06	15.058

From the table it is clear that the effective method of rehabilitation for the corroded beam is by using hybrid laminates along with post tensioning.

Table 4: Comparison of different methods of retrofitting the beam with precrack at flexural zone

Methods of rehabilitation	Ultimate load	Max. deformation
Using BFRP	130.18	7.510
Using CFRP	126.52	9.529
Using GFRP	106.76	7.862
Using post tensiong	273.74	26.028
Using hybrid laminates	174.42	10.573
Using hybrid laminates with post tensiong	285.31	25.998

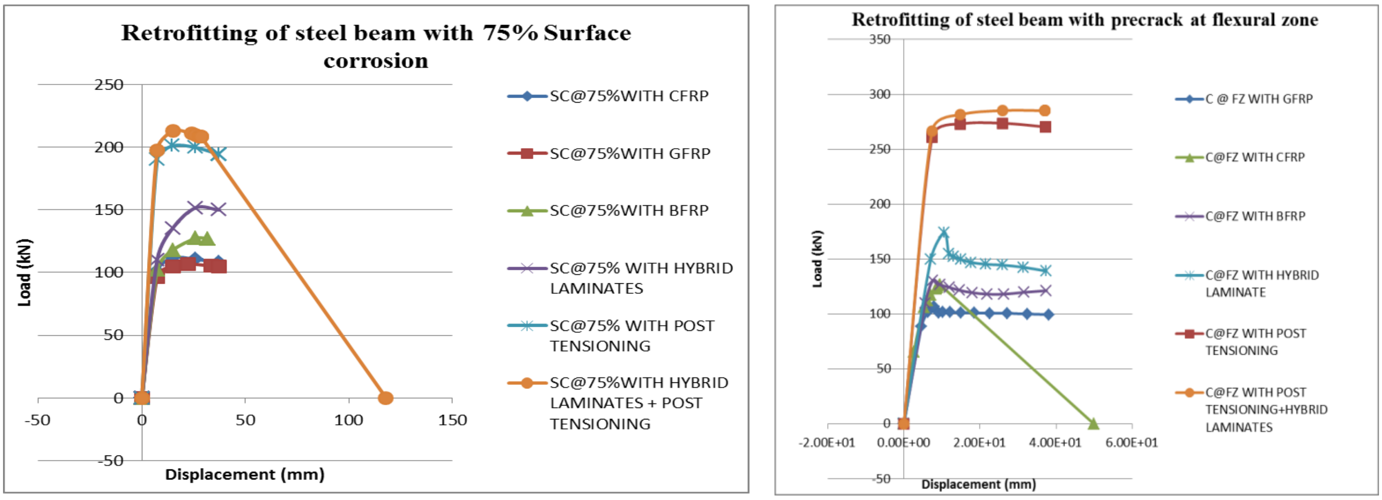


Chart -2: Load Deflection curve of steel beam with different retrofitting methods a)beam with 75% surface corrosion b) steel beam with precrack at flexural zone

4. CONCLUSIONS

In this study, a comparison of different retrofitting methods of steel beam subjected to different levels of corrosion and have precrack at different locations were done and following conclusions were arrived at:

1. Maximum loss in ultimate load is occurred on steel beam subjected to 75% surface corrosion and precrack at flexural zone.
2. Among the retrofitting methods like using CFRP, BFRP, GFRP, post tensiong, hybrid laminate and hybrid laminates with post tensioning, the most effective method of rehabilitation of defected steel beam with crack and corrosion is by using hybrid laminates with post tensioning.
3. On comparison with retrofittingof defected steel beam using hybrid laminates and post tensioning, post tensioning seemed to be more effective.
4. Precrack occurred at flexural zone is more vulnerable to failure than precrack occurred at shear zone

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