FAILURE PREDICTION AND CRACK PROPAGATION WITH STRESS CONCENTRATION USING COHESIVE ZONE FINITE ELEMENT ANALYSIS

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Abstract

In most of the structures, failure occurs due to stress concentrations having notches, sharp corners with different radii's due to the built in geometry of the structure, thereby tend to weaken the structure and the crack may likely to initiate, followed by crack propagation toward the weakest zone within the material. The aim of this research work is to investigate and predict the structural failure with stress concentration having sharp corners with different corner radii's, using the finite element modelling. Stress concentration and crack propagation has been considered in detail.

In this study, cohesive zone model has been considered in greater details to investigate the stress concentration phenomenon using the finite element modelling approach based on exponential load displacement model for interfacial separation of cohesive surfaces produced by the nodal release approach after node merging mechanism.

For each model presented in this research work, a separate user input file has been developed using ANSYS APDL script language, which can later be used for specific change of various variables like crack path, corner radius, meshing, refined meshing, areas and boundary conditions along the specific regions to determine and compare results.

Keywords: *crack propagation, cohesive zone, finite element modelling, stress concentration*

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INTRODUCTION

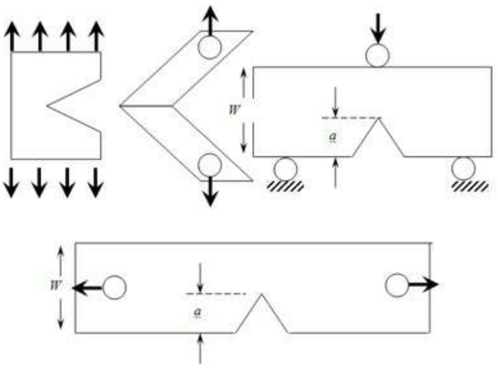
Modern material expertise involve the utilization of components with intricate geometry and are composed of various combinations of dissimilar materials subjected to monotonic and cyclic loading circumstances its life time. The fracture prediction of such components becomes of fundamental importance based on the prediction of reliability of engineering structure. The presence of complex shapes with in the engineering structure is commonly associated with presence of stress concentration which in turn characterizes the weak area of that particular structure with respect to failure initiation of the structure. Hence the weak area with in the particular structure becomes the area of prime interest to get to look deep into the matter.

In any structural components failures resulting from stress concentration phenomenon due to corner radius are crucial in determining the strength of the structure from where the resulting failure will initiate because of the weakest part of the structure. Hence the fracture control of structures is the concerted effort by designers, metallurgists, production and maintenance engineers and the inspectors to ensure safe operations without catastrophic fracture failures. Of the various structural failure modes (buckling, fracture, excessive plastic deformation) fracture is only one. Very seldom does a fracture occur due to an unforeseen overload on the undamaged structure. Usually, it is caused by a structural flaw or crack: due to repeated or sustained normal service loads a crack may develop (starting from a flaw or stress concentration) and grow slowly in size, due to the service loading crack and defect impair the strength. Thus during the continuing development of the crack, the structural strength decreases until it becomes so low that the service loads cannot be carried any more and fracture ensues. The fracture control is intended to prevent fracture due to defects and cracks at the maximum loads experienced during operational service. The high stress level of stress concentrations tends to weaken the structure around its vicinity. Typically these stresses are kind of singular stress fields area generated in the vicinity of geometrical and material discontinuities such as bi material laminate, bi material wedges, cracks interface between two different material. The effect of the elastic moduli has also great influence on the behaviour of the crack and crack propagation. Various studies have been carried out to investigate the matter and being continually done by the author utilizing the latest experimental, analytical, computational and finite element modelling approaches to address and understand the mechanism of non linear approximation. In many cases the standard fracture mechanics approach cannot be directly applied.

Background

Most of the engineering components have to have changes in section and shape which exhibit stress concentration in the vicinity of the discontinuity caused by them that leads to final failure of the component, examples are: Shoulders, Holes, Keyways, Threads, Notches, Irregular Boundaries, Internal Cracks, Voids, Blowholes etc. Various approaches has been presented in this context to predict the behaviour of the stress concentration with the changes in the geometrical discontinuities, a large number of authors have also shown interest in development of the finite element modelling and simulations to analyze the stress field around the keyway corners using the continuum damage mechanics model. The stresses arises due to shrinkage and thermal expansion can cause local stress concentration between keys and keyways that become the cause of initial crack which then propagate for failure of structure (Irwin, 2001 and Tylor, 2006).

The behaviour of the brittle materials under load is not only a function of geometry of the structural component but it also depends the rate of loading and the loading mode for example Bending mode, tensile mode, and compression mode (Aszi and Kolla, 2003). Hence in order to analyze the behaviour of the stress concentration the planned experimental design is necessary and statistical procedures for the experimental design may also be taken into account in order to minimize the errors in experiments. Design of experiment plays important role in two aspects namely in providing the researcher planned tests of experiment and secondly the analysis of variance approach for his designed experiment so as to minimize the possible type of errors by replicating the tests at different time. The machine members often fail under the action of repeated stresses induced due by the application of direct or indirect forces and the failure of the structural member of the machine under the repeated or cyclic stresses is called fatigue failure. Generally, a small crack is enough to initiate fatigue failure, and due to the greater influence of the stress concentration around the crack which in turn tends to grow rapidly and will eventual lead to structural failure because we know that if the stressed area decreases in size, the stress increases in magnitude. Therefore, if the remaining area is small, the member can fail suddenly and the member will fail well below its strength (Budynas, 1999). In order to study the behaviour of cracks simplified models can be made out of the above mentioned models and the loading conditions may be applied in a variety of fashion as shown in Fig 5. Both the approaches either experimental or Finite Element based approach can be used with various choices of Finite Element software. As far as the present context of author's research project we have been taught ANSYS 11 and ABAQUS 6.7, but the author will be utilizing the later one for the research project compilation because of cohesive zone analysis near the crack tip over the characteristic length using the average stress criteria. In order to analyze the criticality of the stress concentrations near the crack tip. The modelling approach is unlike the fracture mechanics approach which utilize the crack size and fracture toughness approach.



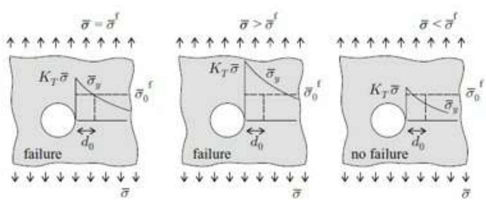
Various approaches to evaluate stress concentration.

Failure criteria

Failure criteria are based on prediction of conditions under which the structural component or material will fail to survive under the application of external load. The Failure is usually classified as brittle or ductile based on the behaviour of plastic deformation observed in the pattern of its deformation. If the failure consists of no plastic deformation the failure will be termed as brittle failure. Maximum Stress Criteria is most simple to use because it utilize the single stress index to determine the failure and this criteria is most commonly used. A Mohr Coulomb failure criterion describes the response of the brittle material to shear stress as well as normal stress. This criteria is used in most of the engineering material in practice for which the compressive strength significantly higher than the tensile strength (Dunn *et al*., 1997).

Point stress criterion

According to the point stress criterion, failure occurs when, at a fixed distance d0 from the hole along the xaxis, σ y is equal to or greater than the stress at failure of the "solid" plate (i.e., the plate without the hole) where is the stress the through the thickness and is average of the normal stress along the x axis and is the strength of the plate (Aszla and Koola, 2003) .

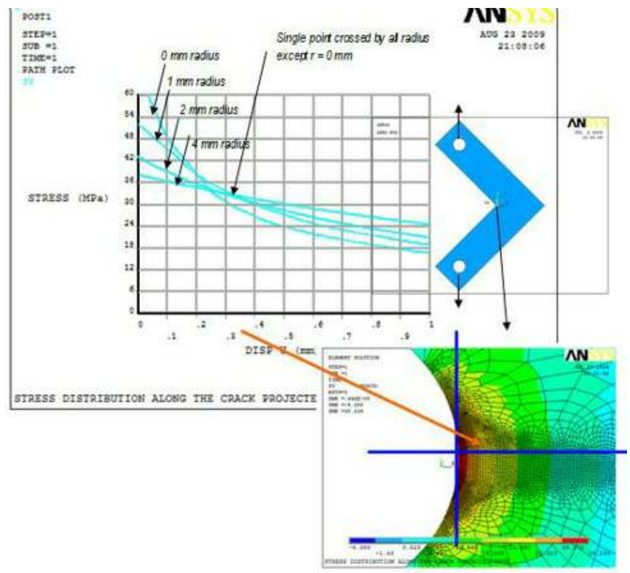


Average stress criteria

According to the average stress criterion, failure occurs when the stress averaged over a fixed distance along the x-axis is equal to or greater than the failure stress of the "solid" plate: Where R is radius of the hole. To apply either of the criteria above, the strength of the solid plate and the stress distribution must be known. This strength is to be obtained by experimental tests in the laboratory. The stress distribution can be determined numerically (Thompson *et al*., 1995 and Tailor *et al*., 2005).

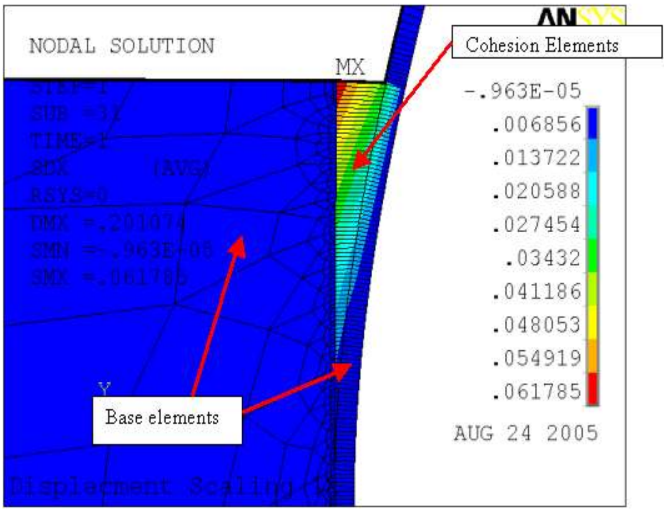
Theory of critical distances

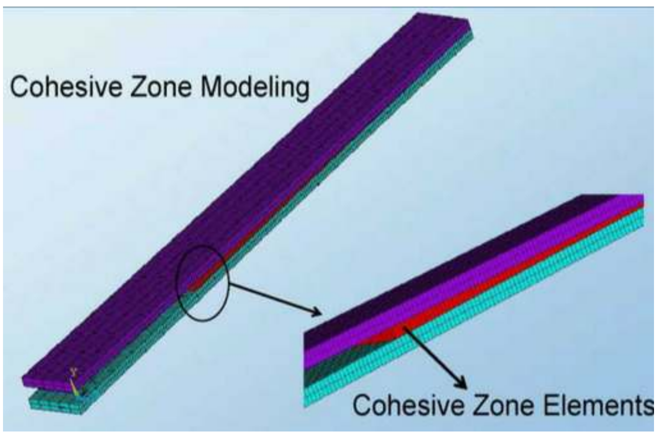
The theory of critical distances (Taylor, 2008) has been used to predict and analyze the stress concentration region. In order to do so the combined plot with in the region of 1 mm has plotted together. The combined plot shows stress displacement curve taken at the fracture load for four different value of the corner radius r. The fact is obvious that the line all cross at a single point, which is equivalent to plain specimen strength.



Cohesive zone modelling

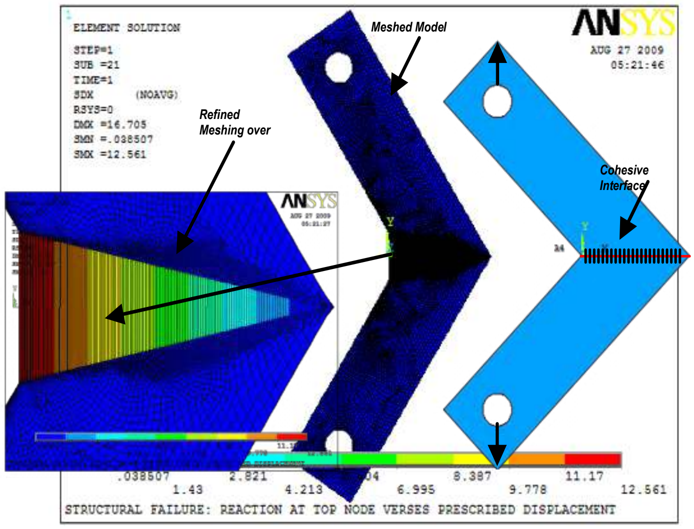
CZM provides an effective methodology to study and simulate fracture in solids. The cohesive zone theory and model allow us to investigate in a much more fundamental manner the processes that take place as the crack propagates in a number of inelastic systems. During crack growth, a fracture process zone exists ahead of the crack tip where micro-cracks or micro-voids initiate, grow, and eventually coalesce with the main crack. The processes in the fracture process zone can be modelled in a simplified way by adopting a cohesive zone model. Hereby, it is assumed that the material along the crack path obeys a specified traction-separation function. The cohesive zone model can be applied for simulating cleavage fracture and micro-ductile fracture. ANSYS 10 introduces the ability to model cohesion. Essentially this allows for the easy creation of initial zero-thickness elements between the boundaries of some “glued” components. These zero-thickness elements will then open up in peel and shear and even “let go” when a maximum stress is encountered. What makes this superior to solid elements with failure criteria or even contact elements with birth and death based on contact results and utilizing restarts is that the formulation allow for modelling the exponential surface potential of an adhesive in deformation. Thus, through specified cohesion element material properties the amount of deformation and subsequent load-sharing with adjacent elements is captured.



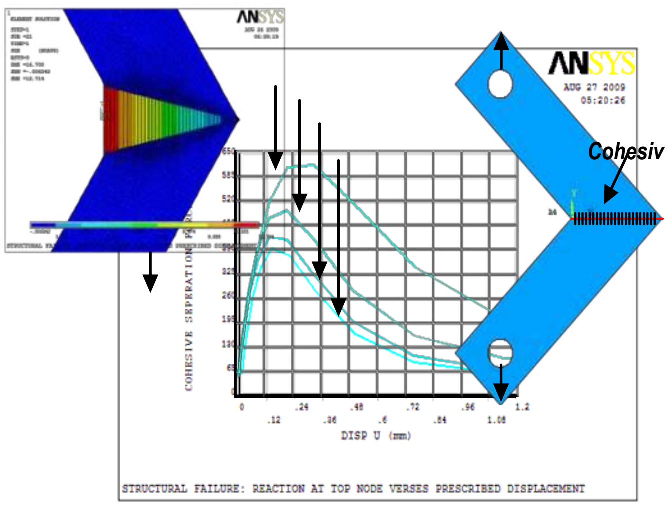


L Sections Samples

L Section model is again considered with the major difference of cohesive zone along the crack propagation in order to visualize the crack propagation and evaluating the load displacement graph with different type of corner radii's having different stress concentration factors. Two different types of models are considered which have different modelling approaches. After prescribing the boundary conditions and loading conditions as given earlier following load displacement graph is obtained, which describes the load

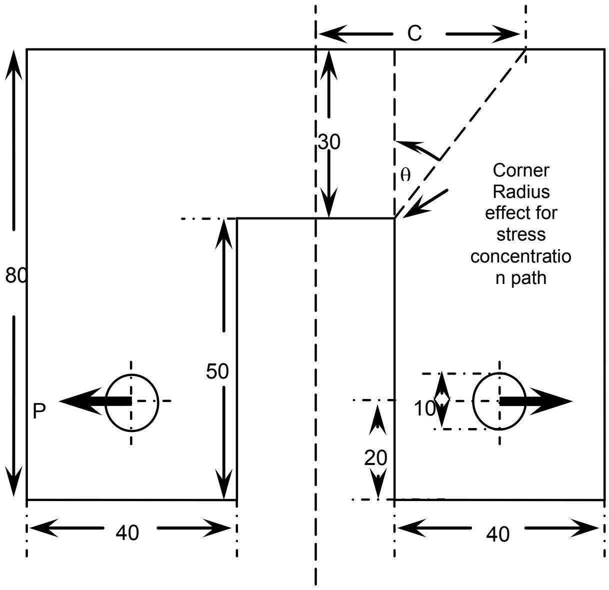


A comparative plot has been presented below which shows the load displacement graphs obtained by running the simulations through ANSYS with the change of the corner radius. The difference is obvious where the required cohesive force need to break the specimen apart is much higher as the corner radius is increased.

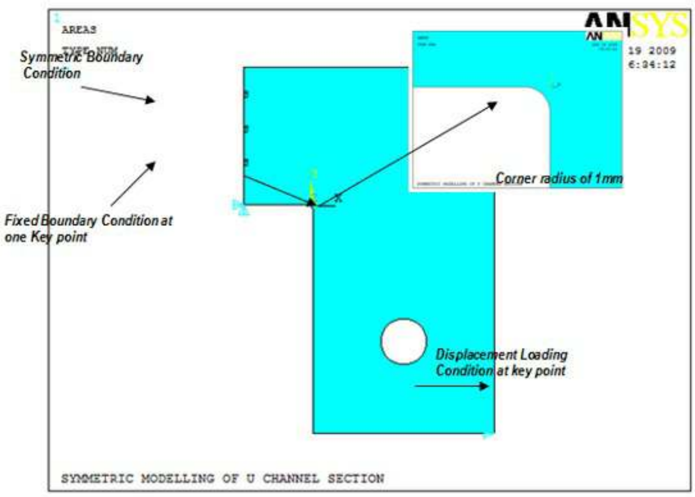


U Channel Samples

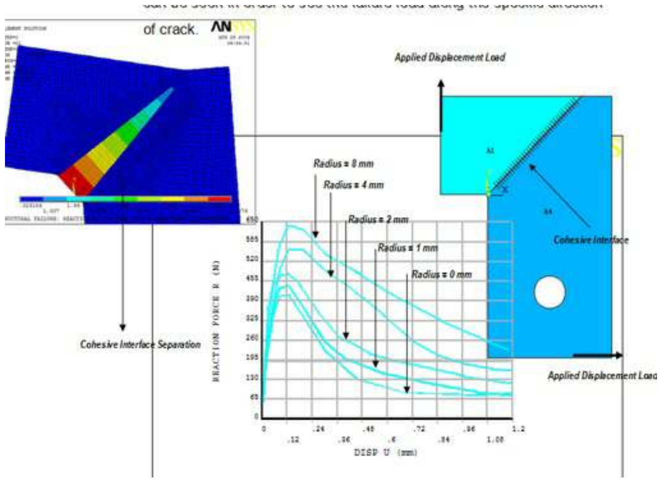
The second model of i.e. channel section specimen as shown in the following figure was modelled for simulating the stress concentration and detail analysis around the corner radius. The variable length C has been defined in this model in order to make the script file available with author, a dynamic one, so that once we know the position of the stress concentration over the corner region then we will be able to plot the stress and load displacement curve along the line.



The half symmetric model of U channel specimen was built using input file given in appendix error! Reference source not found. Following figures shows the important steps in solving and displaying results



The comparative plot is given as under where the quick comparison can be seen in order to see the failure load along the specific direction



Corner Radius	Cohesive Force Required for Structural Failure
0mm	*405.78 N*
2mm	*435.88 N*
4mm	*550.72 N*
8mm	*641.67 N*

DISCUSSION AND CONCLUSION

Finite element modelling of the structural failure of graphite brick slices, was carried out utilizing two different models utilizing the ANSYS metaphysics software. The two models considered are described as follows, along with its further subdivision.

L Section graphite specimen

Determination of stress concentration path structural failure model using cohesive zone at Stress concentration path.

U Channel graphite specimen

Determination of stress concentration path structural failure model using cohesive zone at stress concentration path. The Finite element simulations were divided into two parts, in each case, where at first the initiation of crack will occur and after wards utilization of cohesive zone model for crack propagation along the stress concentration path. Since the path of the stress concentration is the most important objective and in the present discussion the 2D models utilized the mode I failure under the maximum stress criteria, where the failure is likely to start. Therefore in both section the determination of the stress concentration path was the prime objective. In the first case where the L Section specimen was considered, the crack initiation was observed to occur at the mid section of the corner radius with out any change what so ever the corner radius is, where as in the later specimen where the U section specimen was analyzed for crack initiation, the stress concentration path was observed to be changed with change in angle. The resultant values are tabulated here.

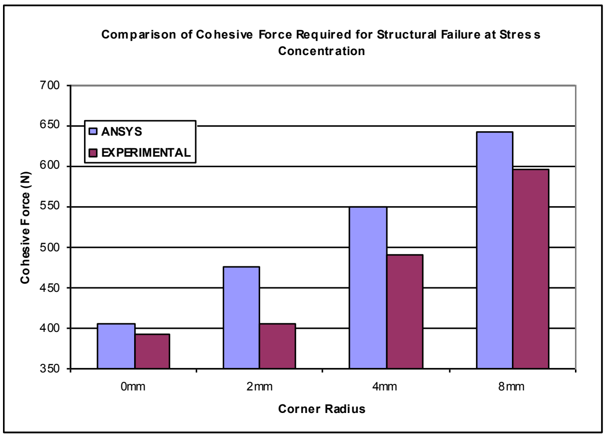
S#	Corner Radius	X	Y	ANGLE
1	*0 mm*	*0.59*	*0.44*	36.71°
2	*1 mm*	*0.98*	*0.591*	*31.09 °*
3	*2 mm*	*2.1*	*1.04*	*26.34 °*
4	*4 mm*	*4.396*	*1.886*	*23.22 °*
5	*8 mm*	*9.7*	*2.866*	*16.46 °*

The second important section of the project in both the specimen used, as described above was to build the failure model that could simulate the structural failure and crack propagation. The cohesive zone approach were adopted, however it is be noted that the cohesive zone elements were not available in the graphical user interface in the ANSYS software so the input file was required in each case. The nuclear graphite appears to fail under the maximum principal stress, i.e. mode I failure. The APDL Script file includes all the input files for both specimens taken in to account.

RESULTS

The estimated structural failure with respect to corner radius again reproduced here briefly and a quick comparison shown in the bar chart below.

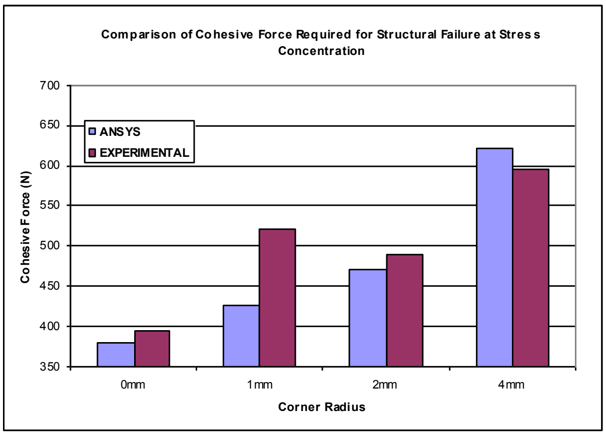
Corner Radius	Cohesive Force Required for Structural Failure	
	ANSYS	EXPERIMENTAL
0mm	*380.56 N*	*394.6 N*
1mm	*425.79 N*	*520.45 N*
2mm	*470.45 N*	*490.66 N*
4mm	*620.87 N*	*595.78 N*



U CHANNEL RESULTS

Table 1: Comparison of Cohesive Force Required for U Channel Structural failure at Stress Concentration

Corner Radius	Cohesive Force Required for Structural Failure	
0mm	*405.78 N*	*390.98 N*
2mm	*475.96 N*	*405.78 N*
4mm	*550.72 N*	*490.67 N*
8mm	*641.67 N*	*595.89 N*



Additionally the project also includes the utilization of the theory of critical distances for comparison within 1mm of the stress concentration path. ANSYS has the great opportunity to develop the refined meshed size over the specified region and obtaining the values of the stress for comparison utilizing up to 32000 data points within the rage of 1mm along the stress concentration path. The comparative plot is very useful in determining the strength of the structure at the weakest region of the corner radius and also for comparison of the stress concentration.

RECOMMENDATION & FUTURE WORK

The study showed the effective use of cohesive zone model on various stress concentration on the basis of different corner radii's. The resultant predictions have good agreement with the available experimental values. Various other models with different materials and element size can be formulated simulated and stress concentration path can be evaluated. Since the crack propagation is the most important phenomenon for the prediction of failure along the weakest part of the structure. More work is required in order to produce other factors like non metallic inclusions, grain boundaries, Slip planes so that the weakest path for the crack propagation could be determined. The study has the wide applications even in the field of bio medical engineering, where human structure containing joints with higher weight lifting capability tends to erode with time due to stress concentration. Certain joints in human body structure needs to be replaced by artificial joints where the present study can be taken into account and can be extended to analyze and simulate various joins with different geometries having specific material. The study can be utilized and extended to any type of the structure with stress concentrations. The prediction of failure can then be formulated based on various available criteria's like maximum stress, maximum strain, Tsi-wu, Tsi-Hill etc.

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