Proc Indian Natn Sci Acad **79** No. 4 December 2013 Spl. Issue, Part A, pp. 553-562

DOI: 10.16943/ptinsa/2013/v79i4/47992

Research Paper

Effect of Non-linear Behaviour of Joints on the Damage Tolerance Analysis in Aerospace Structures**

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(Received 06 April 2013; Accepted 10 April 2013)

This paper presents certain computationally efficient approaches for the non-linear analysis of the most commonly used joints in aerospace structures. Fastener joints were extensively used over years in flight vehicles made of metallic materials and they required non-linear contact stress analysis along the pin-hole boundary. These joints were generally analyzed in the past by expensive iterative methods. Critical problems in fasteners involving interference, push and clearance fit joints are solved in the current work using an inverse method of analysis which dramatically decreases the computational time. This approach made it possible to present the data for all fits in a unified manner. Another type of popular method of joining is using adhesive bonding. Adhesively bonded joints are preferred with the advent of composite structures for aerospace applications. In these joints large displacements occur due to eccentric load path and plastic deformations occurring in the adhesive. Joints between metal-composite, composite-composite joints are analyzed for strength prediction as well as for fatigue de-bond growth. Modified Crack Closure Integral (MVCCI) is used to estimate fracture parameters in the presence of de-bond. Method of characteristic distances is used for static strength prediction. Numerical results on static strength prediction, de-bond growth relevant to Damage Tolerance strategy for these joints are presented. The contents of this paper are a short summary of the work done by the students and colleagues of the author over years. New results generated in the past few years are added.

Key Words : Non-linear Finite Element Analysis; Fastener and Bonded Joints; De-bond Growth and Damage Tolerance

1. Introduction

Fastener and bonded joints are extensively used in large scale structures such as those in aerospace wherein both metallic and composite materials are the primary choice of the designer. These joints are potential locations of stress concentrations or elastic singularities threatening the integrity of the structures. There has been extensive literature in the past for joints in metallic structures [1, 2]. However with the development in technology using interference bolts to improve fatigue life as well as with the advent of novel materials such as composites, the study of joints has again assumed considerable significance. Advanced methods of analysis need be developed to predict residual strength and remaining life of these joints. Fracture mechanics based damage tolerance methods ensure safety of the structures employing these joints in high technology structures. This paper presents an overall appreciation of the issues involved and present certain critical solutions developed for both fastener and bonded joints.

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***Part of this paper is based on the key note address presented at ICCMS 2012 international conference organized by IIT, Hyderabad and other parts were presented at the conference to felicitate Prof. N K Gupta held at New Delhi in September 2012*

Stress analysis based on Finite Element methods and Fracture Mechanics are the basic sciences behind these studies. The key issues are the non-linear behaviour of these joints during the load transfer. Load transfer in fastener joints lead to contact stress non-linearity due to the progressive loss of contact in interference and progressive increase in contact in case of clearance along the pin-hole interface above certain load levels. Adhesive joints between thin adherends such as those used in aerospace cause large rotations leading to geometric non-linearity. Most of the adhesives have well defined yield stress and material non-linear behaviour occurs along the interface. The main aspect of the work is that these types of non-linearity are handled effectively and in a computationally efficient manner.

Fastener joints are the most used in many engineering structures including aerospace. Fig. 1 shows a typical single fastener joint under bearing and bypass loading. The primary stress analysis of these joints with clearance, push and interference pins require a non-linear contact stress finite element analysis. Also due to lack of information on the contact-load behaviour very expensive iterative methods had to be used in the past. An inverse technique has been proposed for the analysis of such problems with contact stress non-linearity and was used [3-5] in the past by the author and his co-workers. This technique is effectively used to generate several solutions of design significance.

With the advent of laminated composite structures adhesive bonding has become popular due to lesser locations of stress concentration. However such a joint is quite suspect of de-bond tolerance. Analysis of these joints requires geometrically non-linear analysis due to large rotations due to the eccentricity of load path. This type of non-linearity is handled using standard methods of analysis [6]. The first part of the studies is static strength prediction. In this case the issue is the presence of stress singularities at the tips of de-bond. The normal method of comparing the maximum stress in the field with material strength properties cannot be applied for this problem. Method of characteristic distances [7] in which stress at (or average stress over) a characteristic distance away from the point of singularity is compared with the material strength to make strength predictions.

The structural integrity of the joints is evaluated using the basic principles of Fracture Mechanics. Several methods were developed in the past to post-process finite element data to estimate the fracture parameters within the realm of linear elastic fracture mechanics. The most popular method for this purpose is the Modified Virtual Crack Closure Integral (MVCCI) which was originally proposed by Rybicki and Kanninen [8] and for 8-node quadrilateral by Buchholz [9]. It was developed further by the author and his co-workers [10-12] and by Raju *et al*. [13]. Fracture parameters at de-bond between the adherends is estimated using MVCCI. This technique is also appropriately modified to be used in the presence of geometric non-linearity. Fatigue analysis is carried out for constant amplitude and variable amplitude spectra to study fatigue de-bond growth. De-bond growth rates were estimated and correlated with fatigue experiments [14]. These studies facilitate the strategy of damage tolerance approach for ensuring the structural integrity in aerospace vehicles.

The current paper presents certain examples of non-linear analysis of typical joints and point out specific conclusions which are of design significance and also relevant to Damage Tolerance evaluation.

Typical structural Joint configurations in fastener and adhesively bonded joints are shown in Figs. 1 and 2. Fastener joint is typically a pin-in-a-hole cofiguration transferring a load P (Fig. 1). The joint considered is a major joint such as wing-root fitting and the pin could be an interference, push or clearance fit. The adhesively bonded joint is a lap joint transferring load across the two adherends (Fig. 2). The adherends could be made of metallic and/or composite material.

2. Non-linear Contact Stress Analysis in Fastener Joints

Fastener joints could be of interference, push or clearance fits. A rigid pin of diameter 2a $(1 + \lambda)$ is introduced into a plate with a hole of diameter 2a. If λ is positive the fit is of interference, λ is negative the

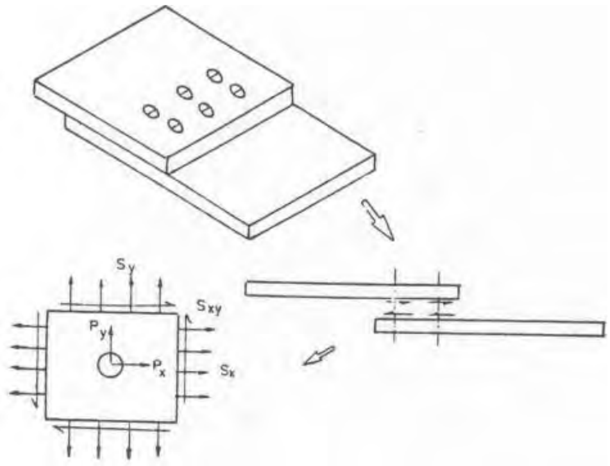


Fig. 1: Single fastener joint under bearing and bi-axial loading

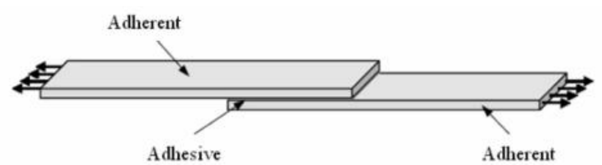


Fig. 2: Adhesively Bonded Lap Joint

fit is of clearance and $\lambda = 0$ is the case of a push fit. A typical lug joint is analyzed using 4-node quadrilateral elements and the finite element mesh is shown in Fig. 3. In the analysis presented the pin is assumed to be rigid. Steel pin in an aluminum lug will have a modular ratio of three between the pin and the lug and the results will be very close to that of a rigid pin. The pin-hole interface is assumed to be smooth in most of the numerical analysis except in one specific example in which the interface was assumed to be

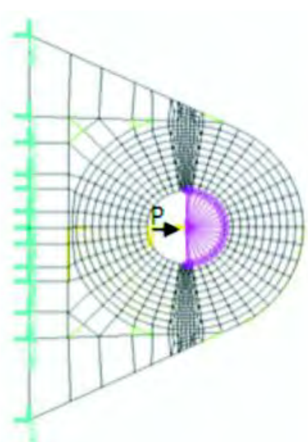


Fig. 3: FE mesh for a typical lug joint analysis

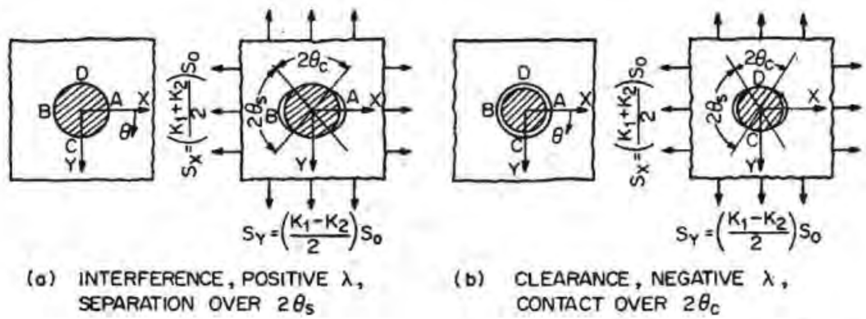
rough. It is possible to consider the cases of interface with finite friction, but this case is not presented in this paper.

2.1 Solutions Using Inverse Technique

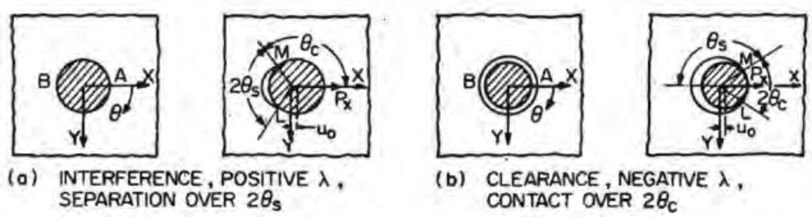
In the process of load transfer it is seen that the pin-plate interface maintains contact as long as compressive stresses exist on the interface. Tension along the interface will cause separation along the interface.

Consider the fastener joint configuration given in Fig. 4. In the first instance the case of interference fit bolt transferring the load is considered. In this case there is complete contact around the interface to start with at zero load. As there is a progressive increase in load transfer on the pin, compression will increase at point A and tension will relax at point B. There will be a load level at which the compressive stresses will be zero at B and the pin-plate interface will separate at point B. Further increase in load will cause the extent of separation to increase symmetrically along the interface. At infinitely large load the extent of separation would reach an asymptotic limit. Such a contact stress problem could be solved by conventional iterative technique where at every point the interface stresses are checked. Contact is specified where the interface stresses are compressive and separation leading to stress free condition is specified where the interface stresses are tensile. This technique is found to be expensive in many problems and much expensive to derive results with parametric variation.

Similarly consider a clearance fit. At zero load there is no compressive contact all round the interface (Fig. 4). When the pin is assigned an infinitesimally small load to be transferred, contact would initiate at point A. Further increase in load would cause the contact to spread on both sides of point A. The extent of contact would reach an asymptotic limit and would not extend beyond this limit. This limiting value corresponds to the extents of contact and separation which will occur at any infinitesimally small load and remain constant with increase in load level for the case of push fit. This throws open the possibility of representing the load-contact relations of all the three fits in a unified manner.



Configuration and coordinate system: Partial contact or separation due to plate load, K_2S_0 positive, hole dia $2a$, pin dia $2a(1+\lambda)$.



Configuration and coordinate system: Partial contact or separation due to pin load, hole dia $2a$, pin dia $2a(1+\lambda)$.

Fig. 4: Fastener Joint Configuration with Partial Contact/Separation for Interference, Push and Clearance pins

A series of these problems are solved using the inverse technique. In these cases the regions of contact and separation are known to progress monotonically about the axis of symmetry. Here the regions of contact and separation are specified and the causative load levels are determined using Finite Element analysis. The case of un-symmetric growth of separation/contact configuration could be handled for the case biaxial loading by making the ends of separation as two parameters and biaxial loading along perpendicular directions as the two load parameters for the causative load levels. Finally in problems where the contact varies arbitrarily the inverse technique will have a limitation.

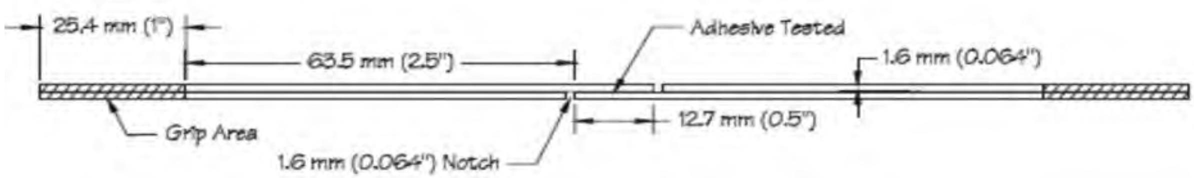


Fig. 5: ASTM D3165 Bonded Joint Specimen

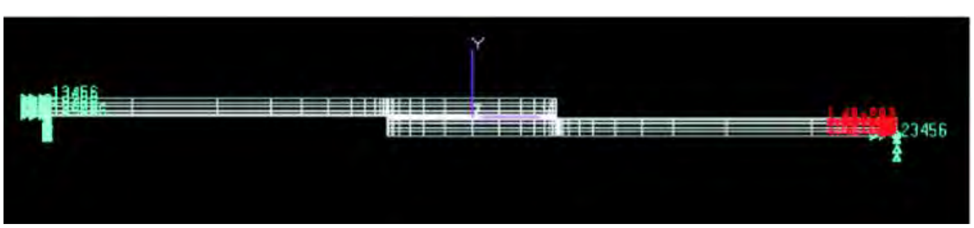


Fig. 6: FE mesh for 2-D analysis

3. Geometric and Material Non-linear Analysis of Adhesively Bonded Lap Joints

Adhesively bonded lap joint shown in Fig. 5 is analyzed using NASTRAN software including geometric non-linear behaviour of the joint. The FE analysis used 4-node quadrilateral elements and the mesh used for the numerical results is shown in Fig. 6.

3.1 Characteristic Distances: Role in Static Strength Prediction

The non-dimensional shear stress distribution along the interface is shown in Fig. 7. The major issue for the strength prediction from the shear and peel stresses at the ends of the lap length is the presence of singularity at this point of peek stresses. For this the method of using the stresses at a characteristic distance away from the singular point is used as described below.

The Theory of Characteristic Distances is well documented by Taylor [7]. Restricting to the type of problems handled in the current paper dealing with 2-dimensional lap joint configurations, one finds that at the end of lap length has a theoretical singularity. Conventional methods of estimating the joint strength based on stress concentrations fail and when the mesh is refined near the ends of the lap length, one finds a sharp rise in stresses in the vicinity of singular point. It is not possible to define a stress intensity factor like in crack problems and so alternate techniques need be envisaged for such problems.

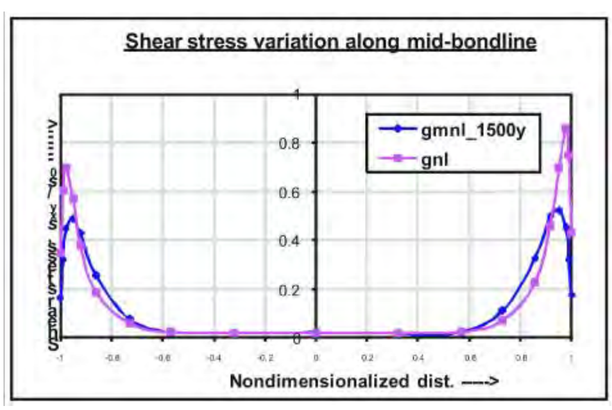


Fig. 7: Shear Stress Distribution along the De-Bond Center Line in Bonded Joint

One method proposed by Whitney and Nuismer [15] was extensively used in the past in which the strength prediction is carried out by comparing the material strength with stress at a point away from singular point. This distance is called as 'Characteristic Distance" and the method is called point stress criterion. Alternately it is possible to do this by averaging the stresses over a characteristic distance from the singular point and compare it with material strength. This is known as average stress criterion. These methods are pictorially described in Fig. 8. In these two methods the characteristic distance values could be different, but they would lead to the same conclusions.

Obviously the estimation of characteristic distances is possible only by comparing the stresses from FE analysis with experimental results on joint strength. When the characteristic distances are obtained over several specimens one needs to go

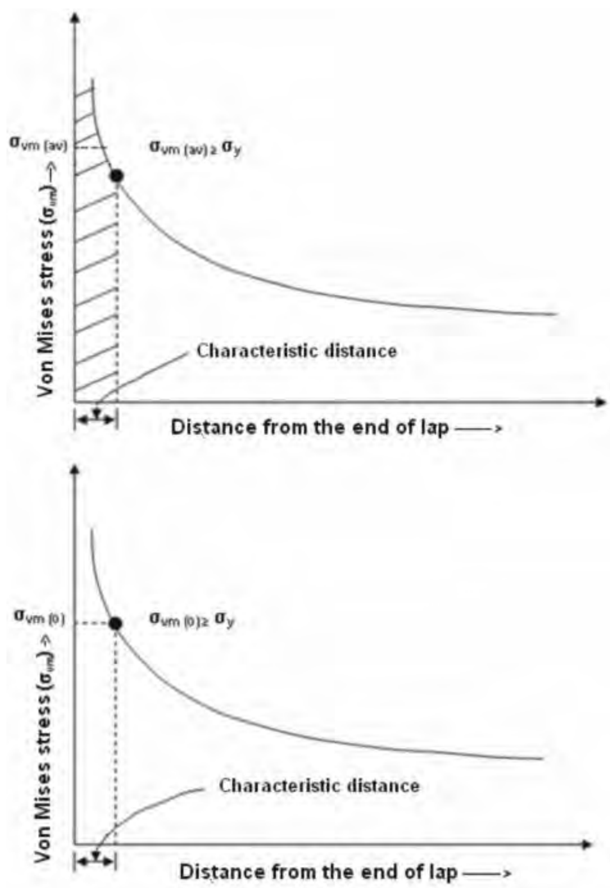


Fig. 8: Average and point stress criteria for strength prediction

through a statistical analysis to arrive at the confidence level with which the mean value could be used for further exercises. Numerical results are presented in this paper to arrive at these figures.

3.2 Experimental and Analytical Studies on Fatigue De-Bond Growth

Fatigue experiments are conducted on specimens based on ASTM standards. Since there were no separate standards for composite materials, the dimensions of the specimen were taken as those specified for metallic specimen. The details of the specimen are presented elsewhere [14]. FE mesh was developed for the joint configuration with cohesive de-bond along the interface between the adherents. De-bond is assumed at the center of the adhesive. Fracture parameters were estimated from the finite element analysis using MVCCI technique given below. Since this configuration has large rotations the forces and displacements used in the MVCCI expressions were taken along and perpendicular to the deformed configuration of the de-bond tip. Using the de-bond growth values and the SERR values a curve fitting was carried out between the de-bond growth per cycle and SERR cyclic range for the fatigue loading.

3.3 Basic Equations of Modified Virtual Crack Closure Integral (MVCCI)

The fracture parameters at the crack tip are the stress intensity factors (SIF's) and the strain energy release rates (SERR's) in various modes of fracture. The current problems primarily deal with mode I (in fastener problems) and mixed mode situation with mode I & mode II in adhesively bonded problems. In MVCCI [8-13] SERR is obtained at any crack/de-bond length by assuming an infinitesimally small virtual crack extension and finding out the work required to close the crack back to the original size. This is expressed for mode I as

$$G = \frac{1}{2\Delta a}\int_0^{\Delta a} \sigma_y V dx \tag{1}$$

This expression can be expressed in terms of Finite Element output as shown in Fig. 9.

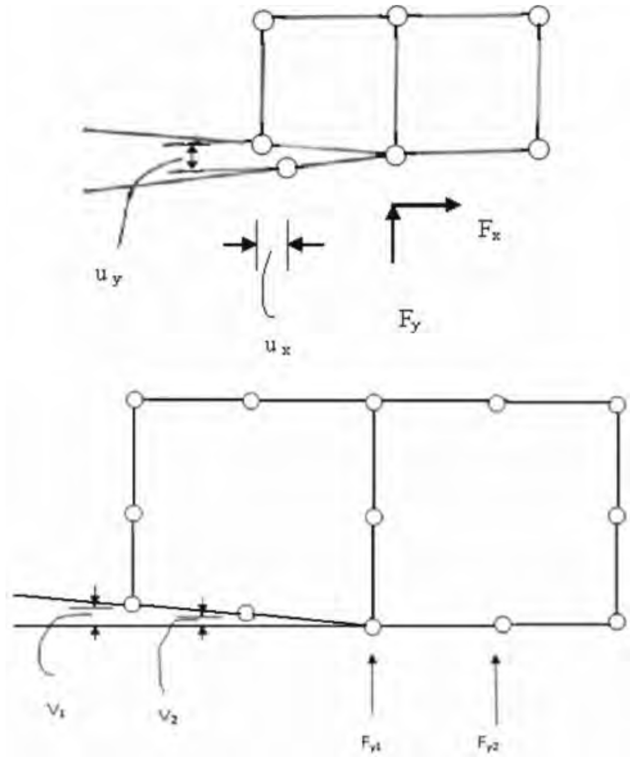


Fig. 9: Nodal forces and displacements used for MVCCI Calculation a) 4-node quadrilateral element and b) 8-node quadrilateral element mesh

For 4- node quadrilateral element

$$G = \frac{1}{2\Delta a} F_y U_y \tag{2}$$

For 8-node quadrilateral element

$$G = \frac{1}{2\Delta a}(F_{y1}V_1 + F_{y2}V_2) \tag{3}$$

The advantage of this method is that it can easily separate mode I and mode II SERR components in case of mixed mode fracture such as that occurs in de-bonded lap joint transferring load. In the case of geometric non-linear deformations, the mode I SERR components should be obtained by taking the components of the forces and displacements along and perpendicular to the deformed de-bond configuration. This is shown in the Fig 10.

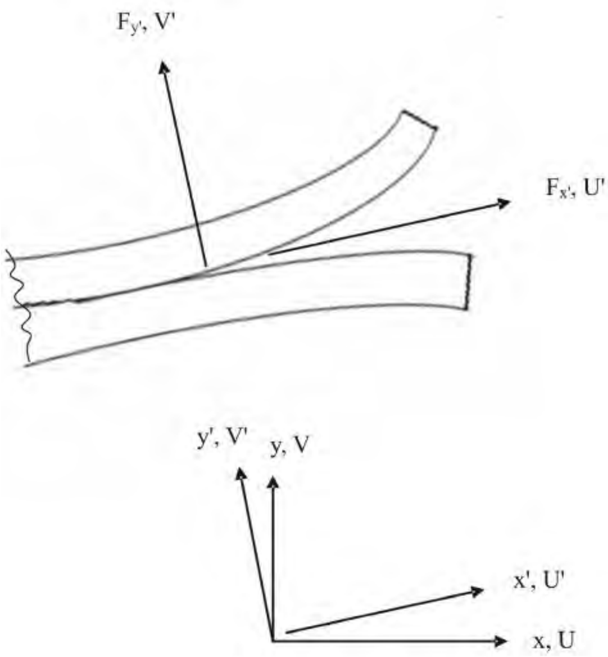


Fig. 10: Forces and displacements along the normal and the center of the de-bond for MVCCI Calculation

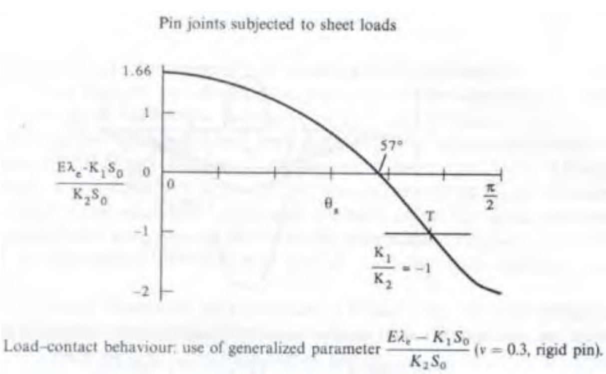


Fig. 11: Load-Contact Relations for plate with By-Pass Loading

4. Numerical Results

Typical numerical results are presented to highlight the approach for various problems of fastener and bonded structural joints in aerospace structures.

(a) Fastener Joints

The fastener joints are analyzed using "Inverse Technique". The case of plate with a hole filled with pin which could be interference, push or clearance fit is analyzed and the load contact relation is shown in Fig. 11. This shows a unified presentation of load-contact relations for all three fits in the same figure. Consider the interference fit. To start with at zero load the interface maintains full contact and pin will separate from the hole boundary at particular load level shown on the y-axis. As the load increases the separation progresses and approaches an asymptotic value at large load level. This is shown by the non-dimensional parameter reaching a zero value.

Consider clearance fit, it has no contact to start with at zero load level. When the joint is loaded the contact spreads and again reaches an asymptotic value shown on the intersection of interference and clearance curves on the axis. This is shown as the point where the interference and clearance curves meet th X-axis. The load-contact relation for case of push fit corresponds to separation and contact indicated on the X-axis and extent of separation/contact does not vary with load level. This way the figure presents the load contact variation for all the three fits in the same figure.

The next aspect is the maximum tensile tangential stress variation along the pin-hole interface with load for interference fit. Due to presence of interference pin there is an initial stress at zero load level as seen in Fig. 12. As the load level is increased the rate of

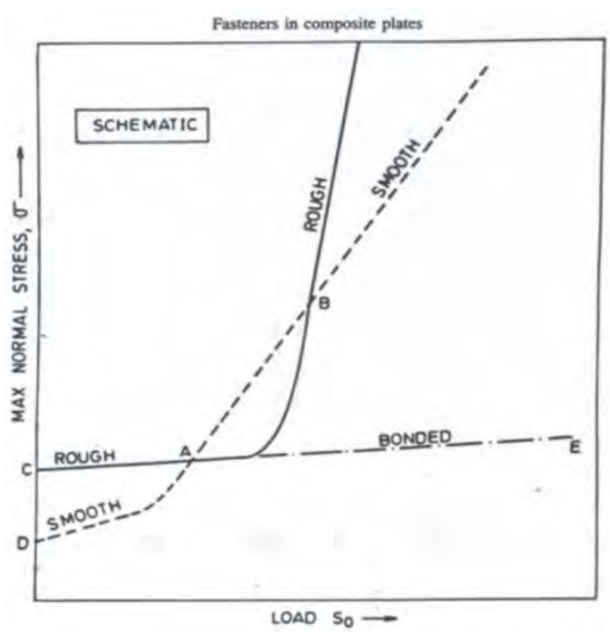


Fig. 12: Variation of tangential stress along pin hole interface for smooth and rough conditions

stress variation with load is minimal till the pin-hole interface separates. Beyond this load level there is a rapid increase of maximum tangential stress at the interface. This fact can be taken advantage to increase the fatigue life of the joint at load levels below those which cause the interface to separate. Also shown is the variation for smooth and rough interface. Obviously the rate of variation of stresses is small for the case of rough interface compared to that of smooth interface due to presence of another path for load transfer due to friction. A fully bonded interface provides this advantage at all load levels.

Bonded Joints

Adhesively bonded lap joint is analyzed using geometrically non-linear analysis and Fig. 13 shows the large deformation of the adhesive line for the case of de-bonded interface. In this case the mode I SERR components should be obtained by taking the components of the forces and displacements along and perpendicular to the deformed de-bond configuration. The deformations are large even in the case of no de-bond.

For strength prediction both shear and peel (Fig. 14) stresses along the interface are used using point and average stress criteria. The figure shows the values reported by point stress criterion. The characteristic distances are arrived at by correlating the FE based stress distribution with carefully conducted experimental programme. This experimental programme is conducted by the author and his co-workers and reported elsewhere [14]. The scatter of the values is shown in Fig. 15 and this was subjected to statistical analysis. From the T-test, it is found that the mean of 2.64 as the characteristic distance could be used for point stress criterion with 95% confidence level. The results match with those presented by Gopalan [16].

Finally, experimental programme was conducted on fatigue de-bond growth on the bonded joint specimen. The de-bond growth results are shown in Fig. 16. From FE analysis SERR component in mode I is estimated and curve fitting is carried out between de-bond growth rates and range of mode I SERR. The results are

$$\frac{da}{dN} = CG_{\max}^{m}$$

where m = 5.845 and C = 2.2 E-15. These results

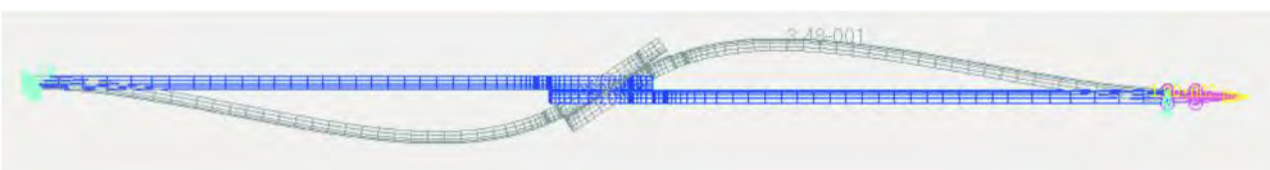


Fig. 13: Large deformation configuration of ee-bonded joint

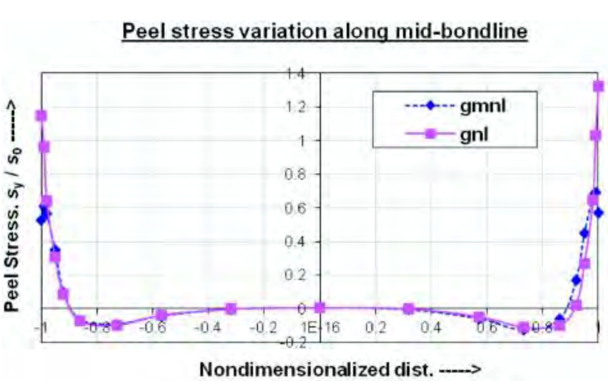


Fig. 14: Peel stress variation used in static strength prediction

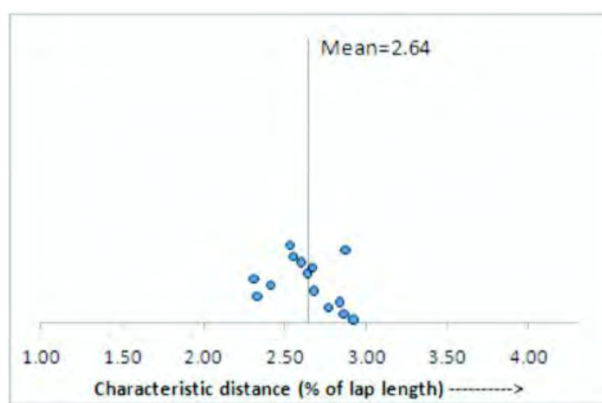


Fig. 15: Characteristic distance variation (Scatter) for 14 specimens by point stress criterion

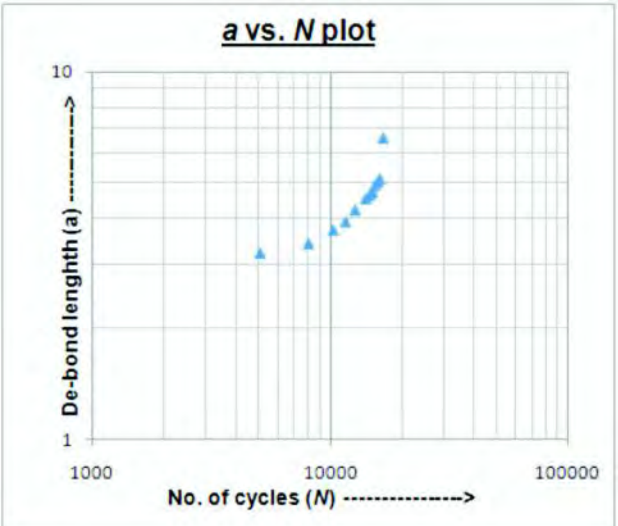


Fig. 16: Variation of De-bond growth with number of fatigue cycles

feed into the Damage Tolerance Analysis (DTA) of primary structural components.

5. Concluding Remarks

Structural Joints are inevitable in large scale structural systems such as those in aerospace structures. The problems of bolted joints with interference, push and clearance fits need non-linear contact stress analysis. The adhesively bonded lap joints need large deformation analysis due to the eccentricity of load transfer. This paper reviewed certain novel methods of analysis of these issues in both types of joints developed by the author and his co-workers over years. Contact stress problems in pin joints are handled by a computationally efficient "inverse technique". In bonded joints the structural integrity related to de-bond growth fatigue experiments were carried out and related to fracture parameters. Strain Energy Release rate was computationally estimated using Modified Crack Closure Integral and this is suitably modified to take care of large deformation. Certain numerical results are presented. These results help in setting Damage Tolerance issues in structural joints in the crucial aerospace components.

Acknowledgements

This paper is written from the contributions of the author, his co-workers and many students. Author would like to acknowledge his teacher Prof. A K Rao, his colleague Prof. T S Ramamurthy and many Ph.D. students Drs. P D Mangalgiri, V A Eshwar, S P Ghosh, H M Aruna, R Gopalan, K Badari Narayana, K K Brahma, K Lok Singh and P K Sahoo for their contributions to the science of Structural Integrity and for helping the author in writing review of their theses work.

References

1. Rao A K Elastic Analysis of Pin Joints *Computers and Structures* **9** (1978) 125-144
2. Harris H G, Ojalvo I U and Hooson R E Stress and Deflection Analysis of Mechanically Fastened Joints AFFDL-TR-70-49, 1970
3. Eshwar V A, Dattaguru B and Rao A K Partial loss of contact in interference pin joints *The Aeronautcal Journal* (1979) 233-237
4. Mangalgiri P D, Ramamurthy T S, Dattaguru B and Rao A K Elastic analysis of pin joints in plates under some combined pin and plate loads *Int J Mech Sciences* **29(2)** (1987) 577-585
5. Ghosh S P, Dattaguru B and Rao A K Load transfer from a smooth elastic pin to a large sheet *AIAA J* **19(5)** (1981) 619-625
6. Zienkiewicz O C and Taylor R L *The Finite Element Method.* Vol. 2. 5th Edn. Butterworth-Heinemann (2000)
7. Taylor D The theory of Critical Distances: A New perspective in Fracture Mechanics, Elsevier, London, 2007
8. Rybicki E F and Kanninnen M F A finite Element Calculation of Stress Intensity factors by a modified Crack Closure Integral *Engng Fract Mech* **9** (1977) 931-938
9. Buchholz F G Improved Formulae for Finite Element Calculations of strain Energy Release Rate by Modified Carck Closure Integral Method. Edited by J Robinson. 4th World Congress and exihibition in finite Element methods, Dorcet, (1984) 650-659
10. Ramamurthy T S, Krishnamurthy T, Badari Narayana K, Vijayakumar K and Dattaguru B Modified crack closure integral method with quarter point elements *Mech Res Communications* **13(4)** (1986) 179-186
11. Badari Narayana K, Dattaguru B, Ramamurthy T S and Vijayakumar K A general procedure for modified crack

closure integral in 3D problems with cracks" *Eng Fract Mech* **48** (1994) 167-176

12. Singh K L, Dattaguru B and Ramamurthy T S Fracture Analysis of delaminated composite panels in compression using numerically integrated MVCCI *Mechanics of Advanced Materials and Structures* **13** (2006) 303-315

13. Raju I S, Crews J H and Amnipour M A Convergence of strain energy release rate components for edge delaminated composite laminates *Engng Fract Mech* **30** (1988) 383-396

14. Sahoo P K, Dattaguru B, Manjunath C M and Murthy C R L Fatigue De-bond Growth in an adhesively bonded single lap joint *Sadhana Indian Academy of Science Journal* **37** (2012) 1-10

15. Whitney J M and Nuismer R J *J Composite Material* **8** 253 (1974)

16. Gopalan R A Study on hygro-thermal effects on advanced composites and adhesively bonded joints, PhD Thesis, Department of Aerospace Engineering, Indian Institute of Science, Bangalore, India (1991).