

# Loading Jig Manufacture to Apply Mixed-Mode Loading to Bonded Structures

Hafiz TA

Department of Mechanical Engineering Sciences,  
Faculty of Engineering and Physical Sciences,  
University of Surrey, Guildford, Surrey, GU2 7XH, UK.

**Abstract** - A simple loading jig has been designed and manufactured. The purpose of the loading jig is to facilitate mixed-mode fracture testing of adhesively bonded Double Cantilever Beam (DCB) joint specimens over a wide range of mode mixities from pure mode I to pure mode II. The loading jig is statically determinate. The specimen loads  $F_1$  and  $F_2$  (loads applied to lower and upper substrate respectively) have been calculated based on conditions of mechanical equilibrium, neglecting shear deformation and assuming that the adhesive layer of the test specimen is very thin. Finite Element Analysis (FEA) has been used to optimise the design. The results for loads acting on upper and lower substrates due to applied load from external source, obtained using established analytical methods and Finite Element Methods (FEM), agree very well over the range of loadings applied by the jig. Same load ratios are obtainable using different supports and point of external force within the jig. Therefore, the jig provides the self verification method as well.

**Keywords** – Mixed-Mode Loading, Pure Mode I, Pure Mode II, Loading Jig, FEA.

## I. INTRODUCTION

A particular issue with the integrity of adhesive joints is the presence of cracks and flaws in the as-manufactured adhesive bondline. The presence of these defects, at least at some scale, appears inevitable and the propagation of such cracks/flaws has the potential to affect the service life of the adhesively bonded joints and even to cause catastrophic failure of bonded structures in service.

Hence, a better understanding of crack propagation behaviour under realistic types of combined (direct and shear stress components) service loading is an important aspect of evaluating the potential performance of adhesively bonded joints [1].

In principle, crack propagation can be described using a fracture mechanics approach [2]. In brittle homogeneous materials, a crack subjected to mixed mode loading will kink in such a way that the crack tip tends to become oriented at right angles to the tensile stress component thereby growing under mode I loading [3]. However, in bonded joints under arbitrary loading conditions, the crack is often constrained within the adhesive layer and can, therefore, be made to grow, at least macroscopically, in the plane of the applied mode II (for shear) or mixed-mode (for tension and shear) loading [4]. Much work has been published to characterise the performance of adhesive joints under mode I loading, but on its own, this does not provide a basis for conservative design under more

complex loadings. Hence the need for mixed-mode fracture characterisation becomes unavoidable.

Many researchers have used a range of experimental techniques to characterise mode I, mode II and mixed mode I/II fracture of adhesive joints and composite laminates but none of these approaches provide a method of characterising material response over the entire range of mode mixities from pure mode I to pure mode II. The method used by [4] appears to be one of the few approaches [5-7] that do achieve this and in that respect it appears surprising that their technique has not been adopted more widely[1].

Hence in the present work, a simple loading jig was designed and manufactured, building on the work in [4] with modifications. FEA was used to optimise the design. The jig enables quasi-static fracture testing of a Double Cantilever Beam (DCB) type specimen over the entire mode-ratio range from pure mode I to pure mode II and is used for fatigue testing as well.

## II. DESIGN AND ANALYSIS OF THE LOADING JIG

### 2.1 Test Method

The purpose of the loading jig is to facilitate mixed-mode fracture testing of adhesively bonded DCB joint specimens over a wide range of mode mixities from pure mode I to pure mode II. The jig, shown in Fig.1 consists of a link arm system that allows the ratio of the forces  $F_1$  and  $F_2$  acting on the upper and lower adherends of the test specimen respectively to be varied by altering the position of the applied load ( $F$ ) along the upper link, i.e. by varying the distances  $S_1$  and  $S_2$ . The column at the right hand end of the specimen enables the specimen to be supported prior to application of load and prevents out of plane displacement during the test. The links in the loading jigs are made of mild steel and dowel pins are used to enable the geometry position to be changed easily.

The uppermost vertical bar is attached to the mechanical testing platform using a pin arrangement. The upper horizontal drilled bar (Part A) is 240 mm long in total and of 40 mm height and 20 mm width. It is designed with holes (from right to left) at 45, 70, 100, 133.3, 165 and 200 mm measured from the centre of the right-hand adjusting pin. These holes enable different mode ratios to be applied. The lower bar (Part B), (440 long x 40 height x 20 depth) is connected to the base plate by Support (A) at one of two locations: either through a pin at D (i.e. the configuration shown in Fig.1) or through a pin at C. The 16 mm diameter holes in the base plate enable the jig to be

attached to the base of the machine. These base plate holes are aligned with the holes in Part A to ensure alignment while applying load during testing.

The remainder of this paper considers the simple mechanical analysis of the loading jig.

### 2.2 Mechanical Analysis of the Loading Jig

The loading jig is statically determinate and the specimen loads  $F_1$  and  $F_2$  are calculated based on the conditions of mechanical equilibrium, neglecting shear deformation and assuming that the adhesive layer of the test specimen is very thin.

It is necessary to take care regarding the sign convention. In particular,  $F_1$  and  $F_2$  are taken as positive when they act in the same direction as the applied load  $F$ . When the Support (A) in Part B is attached by the pin at D as in Fig.1, equilibrium of the upper and lower bars gives

$$F_1 = F \times \left( \frac{S_2}{S_1 + S_2} \right) \quad (1)$$

$$F_2 = F \times \left( \frac{S_1}{S_1 + S_2} \right) \left( \frac{S_4}{S_3 + S_4} \right) \quad (2)$$

When the Support A in Part B is attached by the pin at C, we find that  $F_1$  remains unchanged, but now:

$$F_2 = -F \times \left( \frac{S_1}{S_1 + S_2} \right) \left( \frac{S_4}{S_3 - S_4} \right) \quad (3)$$

Having established the basic relationship between the applied forces, this can be used to find the required configuration of the jig in order to produce a given mode ratio.

## III. LOADING ON THE JOINTS FOR DIFFERENT MODE RATIOS

### 3.1 Pure Mode I Condition

For pure mode I loading of the joint, the applied forces  $F_1$  and  $F_2$  must be equal in magnitude and opposite in direction *i.e.*  $F_1 = -F_2$ . With the pin at C, it follows from Eqs. 1 and 3 that for mode I

$$F \times \left( \frac{S_2}{S_1 + S_2} \right) = F \times \left( \frac{S_1}{S_1 + S_2} \right) \left( \frac{S_4}{S_3 - S_4} \right) \quad (4)$$

From Eq. (4) it is clear that the condition for pure mode I is satisfied when the load is applied centrally to Part A so that  $S_1 = S_2$  and further that Part B is attached to the base through locating Support (A) at position C so that  $S_4 = 0.5S_3$ .

### 3.2 Pure Mode II Condition

For pure mode II condition, there are two loading scenarios which will produce mode II for identical adherend thicknesses in the present jig. Case 1 is when  $F_1 = F_2 = F/3$  the total applied load on specimen is  $2F/3$  and the case 2 is when  $F_1$  is zero while  $F_2 = F/2$  and a shim used transmits half of  $F_2$  to the upper adherend. Hence, the total applied load on specimen is  $F/2$ . These are achieved by pinning support (A) at position D and then having

either  $S_1 = 133.3$  and  $S_2 = 66.7$  (to give  $F_1 = F_2 = F/3$ ) or  $S_2 = 0$  (to give  $F_1 = 0$ ).

### 3.3 Mixed-Mode Condition

Other geometries apart from those described in section 3.1 and 3.2, for pure mode I and pure mode II respectively, enable different mode mixities to be achieved. By combining, Eqs. 1 and 2, for support (A) at position D, we have:

$$\frac{F_1}{F_2} = \frac{S_2}{S_1} \left( \frac{S_3 + S_4}{S_4} \right) \quad (5)$$

While combining Eqs. (1) and (3), for support (A) at position C, we have:

$$\frac{F_1}{F_2} = -\frac{S_2}{S_1} \left( \frac{S_3 - S_4}{S_4} \right) \quad (6)$$

The various pin arrangements and support conditions enable a wide range of intermediate mode mixities to be achieved.

## IV. FINITE ELEMENT ANALYSIS (FEA) OF THE JIG

As the purpose of the loading jig is to facilitate mixed-mode fracture testing of bonded joint specimens over a wide range of mode mixities from pure mode I to pure mode II, it becomes necessary that jig itself should be checked and verified. For this purpose, finite element analysis (FEA) of the loading jig was carried out. It consists of a link arm system which allows the ratio of the forces  $F_1$  and  $F_2$  acting on the upper and lower adherends of the test specimen respectively to be varied by altering the applied load ( $F$ ) position along the upper link, *i.e.* by varying the distances  $S_1$  and  $S_2$  as introduced in section 3.2. All the parameters were kept exactly same as used in analytically designed jig. The study used elastic 4-noded (SHELL 63) elements in which key option 3 was taken as zero *i.e.* including extra displacement shapes. Keeping the elements as quadrilateral means they generate more accurate results for bending and membrane stresses. The material responses were taken as linear elastic and isotropic using material constants of 210 GPa and 0.3 for Young's modulus and Poisson's ratio for mild steel respectively.

To represent the holes in the upper horizontal bar and elsewhere which enable different mode ratios to be applied, hard points were applied and to represent the pins in the link arm, coupling option available in ANSYS was used.

The jig was modelled successfully. Fig. 2-4 show 3 cases where load is applied to only one arm of the DCB specimen. So providing same load ratio, it can be seen that the deformation is same in all the cases. This was represented in section 3.3 under mixed-mode condition that when support A is at C and  $S_1 = 0$  mm and  $S_2 = 200$  mm for one case and for second case when support A is at D and  $S_1 = 0$  mm and  $S_2 = 200$  mm and for third case when support A is at C and  $S_1 = 200$  mm and  $S_2 = 0$  mm. As in all the above three cases, the forces experienced by the

specimen are same so the material response should remain same as far as specimen geometry remain same. Figs. 2 and 3 show clearly that as the forces on the lower adherend will be zero, the lower adherend has zero displacement. While in third case (Fig.4), the force on upper adherend is zero hence in this case, the displacement is zero for the upper adherend.

Fig. 5 represents case 2 for pure mode II. As described in section 3.2 half of the force on the lower adherend will be transferred to the upper adherend via the shim used. To meet this situation, the contact between the lower and the upper adherend was made using contact 172 and target 169 elements. So the force on the lower adherend is transferred to the upper adherend to achieve pure mode II case 2 (same magnitude and direction of forces on both adherends).

The forces on respective nodes for other configurations of the loading jig were checked and these were exactly same as those obtained from analytical expressions derived in section 3.3 for  $F_1$  and  $F_2$ .

### V. CONCLUSION

The loading jig facilitates mixed-mode fracture testing of adhesively bonded DCB joint specimens over a wide range of mode mixities from pure mode I to pure mode II. Different combinations of support point C and D provided a wide range of load ratios. Therefore, a single experimental loading jig is sufficient for a wide range of mode mixities from pure mode I to pure mode II. The safety of different parts of the jig was checked successfully.

With the help of the present jig, it is possible to say that not only the supports at C and D points but also the spacing in the upper bar are critical to obtain different combinations of load ratios.

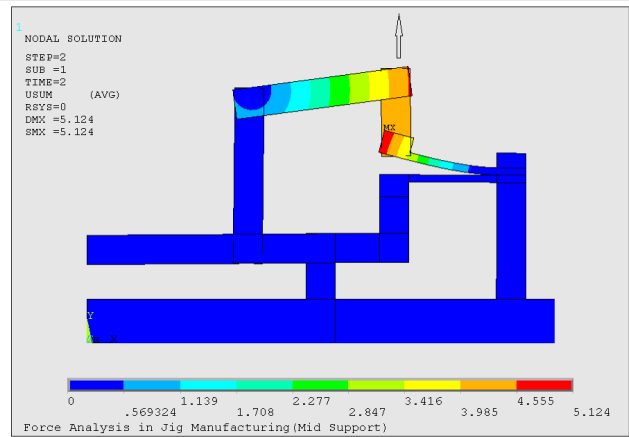


Fig.2. Specimen response when supported at C ( $F_1/F_2=\infty$ ) and  $S_1=0$  and  $S_2=200$

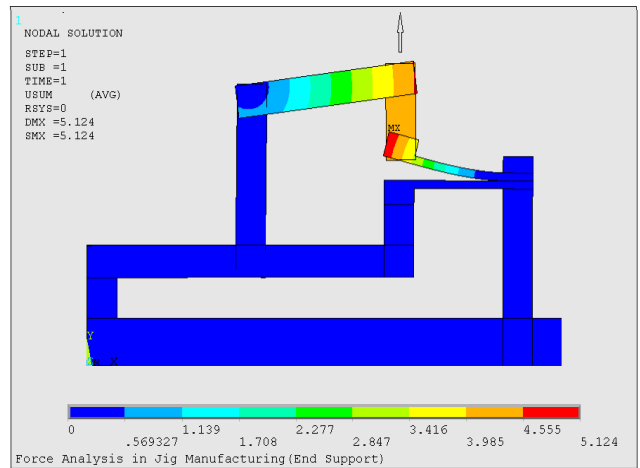


Fig.3. Specimen response when supported at D ( $F_1/F_2=\infty$ ) and  $S_1=0$  and  $S_2=200$

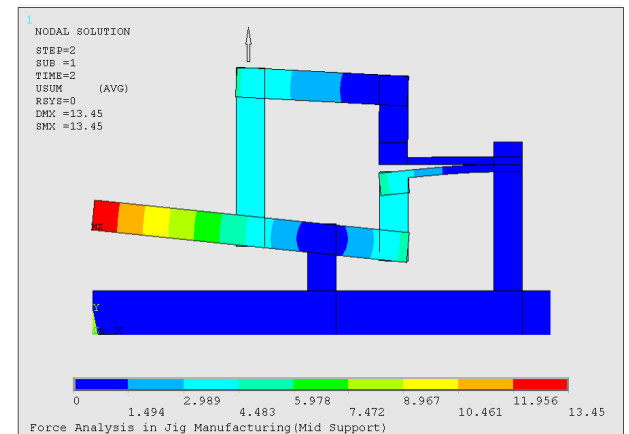


Fig.4. Specimen response when supported at C ( $F_1/F_2=0$ ) and  $S_1=200$  and  $S_2=0$

### APPENDIX

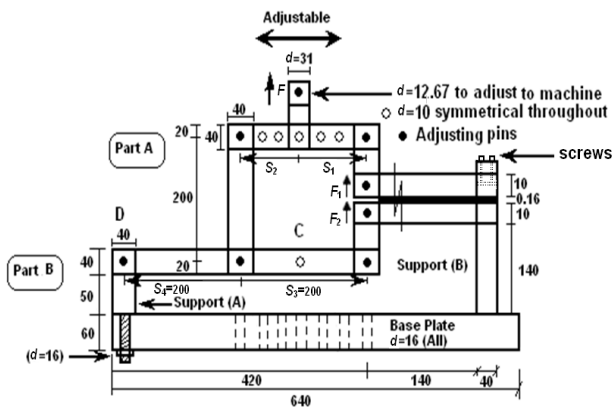


Fig.1. Schematic diagram of the load jig (all dimensions in mm)

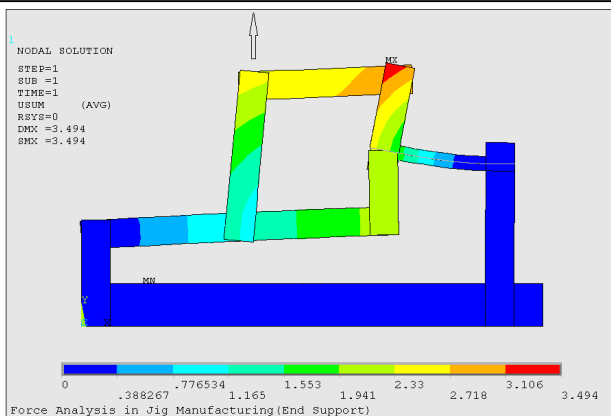


Fig.5. Pure mode II (With contact between adherend)

## REFERENCES

- [1] H. T. Hafiz, M. M. Abdel Wahab, P. A. Smith and A. D. Crocombe, "Mixed-mode fracture of adhesively bonded metallic joints under quasi-static loading", *Engineering Fracture Mechanics*, Vol 77, 2010, pp. 3434-3445.
- [2] G. Fernlund and J. K. Spelt, "Failure load prediction of structural adhesive joints: Part 2: Experimental study", *International Journal of Adhesion and Adhesives*, Vol,11, 1991, pp. 221-227.
- [3] J. W. Hutchinson and Z. Suo, "Mixed-mode cracking in layered materials", *Advances in Applied Mechanics*, Vol 29, 1992, pp. 63-191.
- [4] G. Fernlund and J. K. Spelt, "Mixed-mode fracture characterization of adhesive joints", *Composite Science and Technology*, Vol, 50, 1994, pp. 441-449.
- [5] H. L. J. Pang and C. W. Seetoh, "A compact mixed-mode (CMM) fracture specimen for adhesive bonded joints", *Engineering Fracture Mechanics*, Vol,57, 1997, pp. 57-65.
- [6] N. Choupani N, "Mixed-mode cohesive fracture of adhesive joints: Experimental and numerical studies", *Engineering Fracture Mechanics*, Vol,75, 2008, pp.4363-4382.
- [7] G. V. Marannano, L. Mistretta, A. Cirello and S.Pasta, "Crack growth analysis at adhesive-adherent interface in bonded joints under mixed-mode I/II", *Engineering Fracture Mechanics*, Vol, 75, 2008, pp.5122-5133.

## AUTHOR PROFILE

### Dr Hafiz Ali

completed his BSc with Honours in Industrial and Manufacturing Engineering (IME) from University of Engineering and Technology (UET) Lahore, Pakistan in 2004. He then secured M.Sc. with Merit in Advance Manufacturing Management and Technology (AMMT) from University of Surrey, UK in 2006 and PhD in 2011 from the same University.

Hafiz is currently working on an EU funded consortium involving developing nonlinear ultrasonic techniques to allow the determination of bond strength in composite structures. The key research challenges are interpreting the complex nature of the transmitted nonlinear signal and optimizing the operating point selection for thin specimens. Main challenges include: Experimental demonstration of various nonlinear ultrasonic techniques in thin specimens, Development of models to allow easy selection of a guided wave operating point for inspection of thin components and Usage of nonlinear guided wave inspection techniques to investigate the levels of nonlinearity present in thin composite specimens of varying bond strength. His full profile can be viewed from the following URL:

<http://www.bristol.ac.uk/engineering/people/hafiz-t-ali/overview.html>