CREEP IN BONDED COMPOSITE JOINTS

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Abstract

Adhesive lap joints can suffer from creep elongation under conditions of cyclic loading. This creep is generally resisted by providing the joint with a sufficiently long overlap to preserve a low stress region in the centre of the joint. When loading is released, these joints exhibit a time dependent movement towards their previous unloaded length. Finite element analysis has been used in the prediction of creep under short term cyclic loads. An investigation into the mechanisms for creep and creep reversal in adhesive double strap joints is presented, together with an evaluation of the importance of the stiffness of the adherends in this process.

A mechanism for the reversal of creep in the ends of the joint overlap has been identified. This comes into play when the joint is unloaded, and relies on the establishment of a new equilibrium between the deformed adhesive and the adherends.

1 Introduction

The use of adhesives as an alternative to mechanical fastening in aerospace structures has been a topic of research for many years. Adhesive joining methods have a number of advantages over traditional mechanical methods such as riveting and bolting. These include an increase in damage tolerance, transfer of stress over a region rather than at distinctive points leading to small stress concentrations, and excellent fatigue properties. A disadvantage associated with the use of adhesives is that creep has been known to occur within joints, leading to elongation and possible creep rupture if not addressed.

Data related to the prediction of creep can be time consuming to accumulate. However, using careful joint design, and techniques such as finite element analysis, it is possible to predict both short and long term behaviour. The mechanisms associated with creep of joints will be discussed, and inbuilt mechanisms for reversal of creep will be identified.

2 Design methodology

Final application of joints must be considered carefully in the design process. The first step is to evaluate the highest expected stress in the panels requiring joining. The joint should be able to sustain loads of this magnitude or higher[1]. A load factor is then applied in order to determine the design stress, or the n=1 case. This is the most common loading applied to the structure, and the only loading expected to be sustained for prolonged periods. Consideration must also be given to the temperature at which the load will be applied. Higher temperatures will generally promote greater levels of creep. A conservative estimate would require that the n=1 case be examined at the highest temperature in the operating range of the joint. This has been chosen as the load condition at which to design the joint with respect to creep resistance. If a higher level of stress were to be encountered by the joint, the edges of the adhesive would sustain higher levels of plastic deformation, changing the expected levels of creep.

A common method for the design of a creep resistant joint is to have sufficient overlap length such that the lowest shear stress in the centre of the joint is one-tenth that required for adhesive yield[2]. Other design recommendations require that the overlap length be a multiple of the external panel thickness. In the case of a double lap joint, it is recommended that the multiple be thirty times[3].It will be shown that whilst these guidelines have merit, there are some factors which will reduce their effectiveness under creep loading conditions, such as a gradual increase in the central shear stress with load cycle, and a variation in shear stress profile with joint stiffness.

While it is common to load a joint for a number of months to years, and measure joint length change, this may lead to inaccuracies in the expected levels of creep if applied directly to a structure encountering cyclic loads, such as the joints found in aerospace structures. Cyclic creep predictions were chosen as the most suitable method for evaluation of time dependent changes in the joint configuration. The objective of this research was to examine the effect of changing the basic characteristics of the adherend of a joint under cyclic creep loadings. These characteristics include thickness, material properties and length.

3 Experimental procedures

The method of prediction requires that some data be predetermined for placement into a finite element model. This includes viscoelastic properties as determined through stress relaxation tests, and stress-strain data for the adhesive found through thick adherend tests. Materials used in experimentation were Cytec FM1515-3M thermosetting epoxy adhesive, and Cytec T300/Cycom970 carbon fibre/epoxy composite system for adherends.

3.1 Short term stress relaxation tests

Viscoelastic properties of the adhesive were determined through the use of short term stress relaxation tests[4] on double strap joints. The joint configuration used in this test is shown in Fig. 1. An adhesive layer thickness of 0.15 mm was used. A $[0/90]_{14}$ laminate configuration was used for the central adherend, and a $[0/90]_{7}$ for the outer straps. A crack opening displacement (COD) gage was placed in the centre of the joint, in between the two overlap regions. This was used to maintain a constant displacement over the test period of 3 hours at a constant temperature of 71ºC.

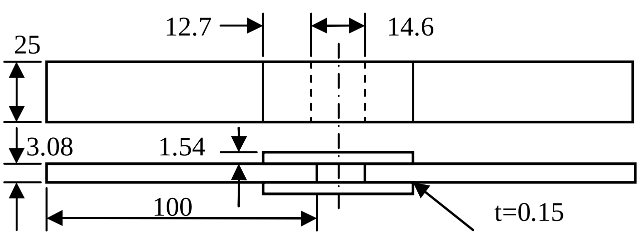

Fig. 1: Short term stress relaxation specimen. All dimensions are in mm.

Over this length of time the force was recorded at constant displacement. By converting the force to an average stress, the initial shear modulus was determined. Regression techniques were then employed in order to determine the decrease in modulus as a function of time. This takes the form of a Prony series.

3.2 Prony series

The Prony series is analogous to a single spring, representing the initial observed elasticity of the material, with a number of dashpots connected in parallel, which represent the time dependent reduction in modulus. It is generally represented with reference to shear modulus and makes use of the Boltzmann Superposition Principle[5]. Because the Prony series represents viscoelasticity, the associated Poisson's ratio follows a flow rule, and is therefore set to 0.5. The Prony series takes the form:

$$G(t) = G_0 + \sum_{i=1}^{n} G_i e^{-\left(\frac{t}{\lambda_i}\right)} \qquad (1)$$

Where G is the shear modulus at time t, and G_0, Gi and λi are constants.

3.3 Experimental results

The terms for FM1515 under an average initial stress of 14MPa are summarised in the Table 1. The resultant time dependent modulus is shown in Fig. 2.

Table 1: Prony series constants for FM1515.

i	λi	Gi
0		255.0632
1	149.503	30.1872
2	1604.53	22.444
3	57583.6	54.6483
4	1000000	8.02769

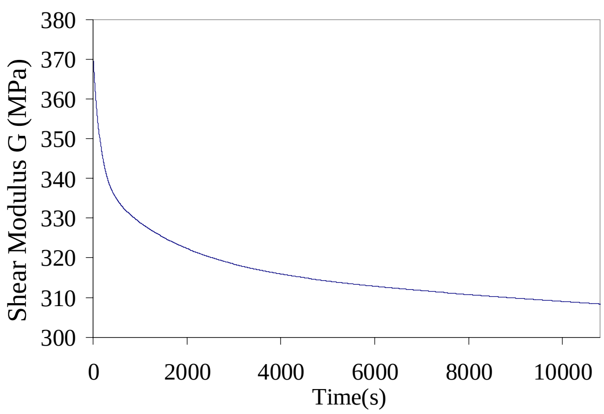

Fig. 2: FM1515 time dependent shear modulus.

Table 2: Properties for FM1515 at 71°C.

Property	Value
E	1 GPa
ν_{12}	0.35
σ_y	26.5 MPa
σ_f	49.3 MPa

Table 3: Properties for T300/Cycom 970 at 71°C.

Property	Value	
E_{11}	60 GPa	$G_{12} = 0.048\ E_{11}$
E_{22}	3 GPa	$G_{23} = G_{12}$
E_{33}	60 GPa	$G_{31} = 0.052\ E_{11}$
ν_{12}	0.2	$\nu_{23} = \nu_{12}$
ν_{31}	0.04	
σ_f	650 MPa	
Property	Value	

4 Finite Element Modeling

Finite element modeling was used for the prediction of joint creep and elongation under the application of cyclic load. MSC.Marc was used because of its good non-linear analysis capability and implicit algorithm for time dependent behaviour to model creep. This was required due to the viscoelastic-plastic properties of the adhesive.

A double strap joint of infinite width was modeled using symmetry conditions. The mesh is shown in Fig. 3. One of the xy faces was prevented from having any z motion. The opposite side was constrained to remain planar. This made it possible to use a single element across the width of the joint without the loss of accuracy. The width of the element was set to 1 mm in the z-direction. The thickness, T, as shown in Fig. 4 is equal to the number of plies times 0.22 mm. L is the stated overlap length. All modeled laminate configurations are oriented in the [0/90].direction.

Viscoelastic properties were entered for the adhesive material through the use of the Prony series detailed in the previous section. Other material properties were entered for the adhesive and composite as determined at 71°C. Loading was sustained for 1 hour. Following this, the loading was reduced to 1% of the sustained loading. This level of loading was found to have little effect on observed stress distributions as compared to unloading to a zero applied stress. This was held for 10 minutes. A total of ten load cycles of this type were simulated in the finite element analysis.

The mesh was carefully designed in order to capture the shear distribution at the ends of the overlap. This required a higher element density in these regions. The number of elements was slowly reduced between the ends and the centre of the overlap region. A total of four elements was placed through the thickness of the adhesive. Ten elements were placed through the thickness of the adherends in order to obtain a reasonable aspect ratio at the interface with the adhesive. These had a bias towards the adhesive material. Composite elements supplied by MSC.Marc were assigned to the mesh representing the adherends.

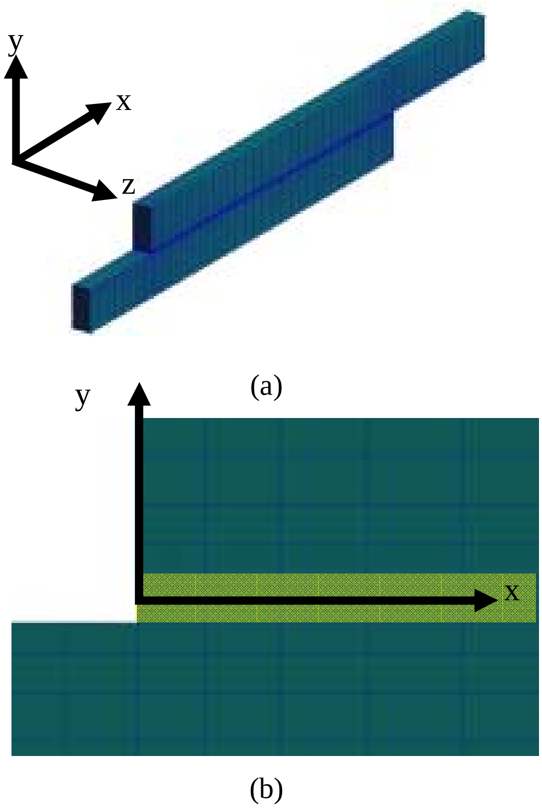

Fig. 3: Finite element model; (a) Whole model; (b) Overlap end with origin.

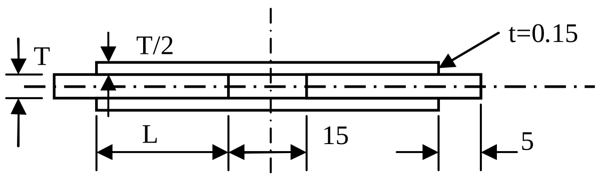

Fig. 4: Joint geometry used in FEM. All dimensions are in mm.

It should be noted that even with the mesh refinements towards the ends of the joint, there was still a positive shear stress present when the joint was loaded. Since this is a non-traction boundary, this is not strictly correct. The mesh was designed, however, to have some reduction in the shear stress towards the ends of the joint after a shear peak had been located.

A direct stress was applied to one end of the joint. This was set to 166MPa in the joint with the 14-ply central adherend, and 116.2MPa in the 20-ply adherend. The reason for this difference was to ensure that an equal shear force was being tracked through the adhesive. Some 20-ply joints also had a 166MPa stress applied for the purposes of comparison.

5 Results of finite element analysis

The effect of variation in joint adherend stiffness due to both material property and thickness variation, and joint length will be discussed in terms of the shear stress distribution upon initial loading. No variation in bond thickness is considered. All stress distributions reported are along the centerline of the adhesive layer as identified by the x-direction in Fig. 3.

In addressing the joint, reference is made to the entire double strap joint shown in Fig. 4. For discussion of stress distribution, the adhesive layer is considered. The area where the central adherend is connected to the outer straps has been termed the overlap region. When the central adherend exists outside of the overlap regions it will be referred to as the external panel.

5.1 Effect of adherend material stiffness

The adherend stiffness can be changed through the variation of the materials elastic properties. This causes a change in the stress distribution in the overlap region as shown in Fig. 5 and Fig. 6. All joints examined had a stress of 166MPa applied.

A more flexible material allows shear stress peaks to be clearly defined. These can be found to exist at a distance in the order of one bond line thickness from the extremes of the overlap. In the case where the adherend stiffness was increased to a very high value, the shear stress was almost uniform across the entire overlap. When the adherend stiffness was reduced to a similar value as the stiffness of the adhesive, there was a very large shear stress at the overlap extremes, followed by a rapid decrease in stress. This situation presents the lowest shear stress at the overlap centre.

The general trend is that with an increase in material stiffness, a more uniform shear distribution is shown to exist across the overlap. As the stiffness is reduced, higher shear stress and levels of yield occur at the overlap extremes, and a lower shear stress occurs at the overlap centre.

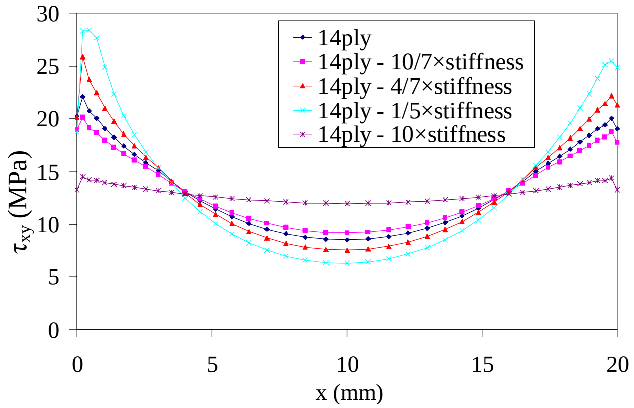

Fig. 5: Effect of material stiffness on shear stress

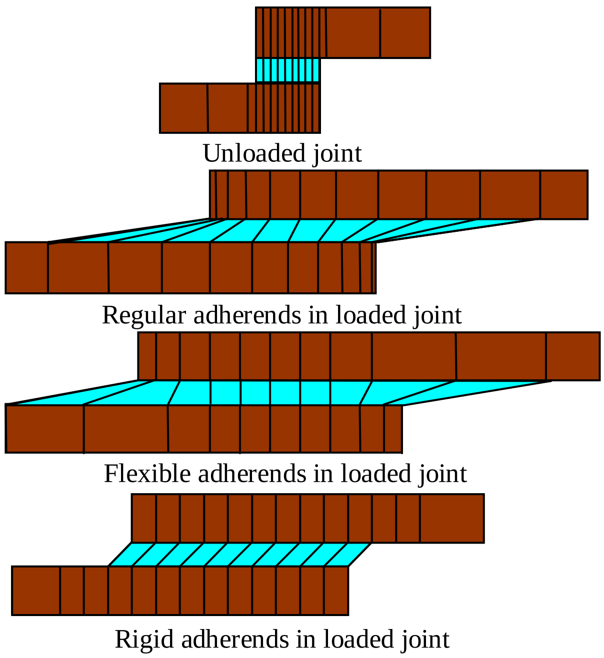

Fig. 6: Effect of adherend stiffness on adhesive strain

5.2 Effect of adherend thickness

The second method of changing the adhered stiffness is to use the same material, but vary the thickness. It then follows that it should be possible to obtain an equal stiffness in an adherend constructed from a stiff material and an adherend constructed from a more flexible material, by increasing the thickness of the flexible adherend.

The two stiffening methods have been compared. The 20-ply adherend has the base material properties. The 14-ply adherend has had its elastic and shear moduli multiplied by 20/14.

In order to make this comparison effective, it was required that the same shear force be tracked through the adhesive. A stress of 116MPa was applied to the 20-ply adherend, whereas the 14-ply adherend maintained the use of a 166MPa stress. For the purpose of comparison, an applied stress equal to that applied to the 14-ply adherend has also been included for the 20-ply adherend.

The shear stress profiles of the 14-ply joint with modified stiffness properties under 166MPa, and the 20-ply joint under 116.2MPa are approximately the same. There is a slightly larger shear stress present at the centre of the 20-ply joint, which leads to a reduction in the shear stress peaks found at the sides of the joint. This is shown in Fig. 7. This is evidence that extension of the adherends during loading plays a large part in the observed shear stress distribution. An increase in peel stress can also be found at the ends of the 20-ply overlap. This is because the offset of the load path entering the 20-ply joint is larger than in the 14-ply joint. Application of 166MPa to the 20-ply joint leads to a clear increase in the shear stress at all points along the joint.

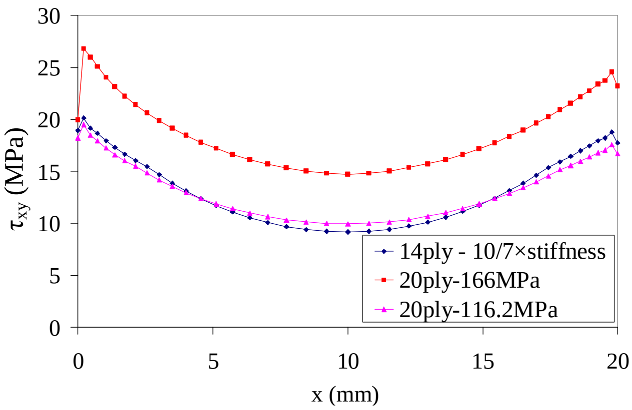

Fig. 7: Effect of thickness on shear stress

5.3 Effect of joint length

The results of the variation of joint length under a constant applied load are presented in Fig. 8. The shear stress profile towards the ends of the overlap is largely unchanged with length. This is due to the adherend playing a large part in the shear stress profile. Under a given direct stress, the external panel has a tendency to strain to a level independent of the joint length. This reasoning extends into the extremes of the overlap. Given that an elastic region can still be found in the centre of the overlap, the only region that is expected to be affected by the lengthening of the joint is the shear stress in the centre, which must balance out the force not transferred between adherends at the ends of the overlap.

A slight increase in the peel stress at the ends of the overlap has also been found to occur with shorter lengths, and this is a result of tendency for the joint to attempt load path alignment.

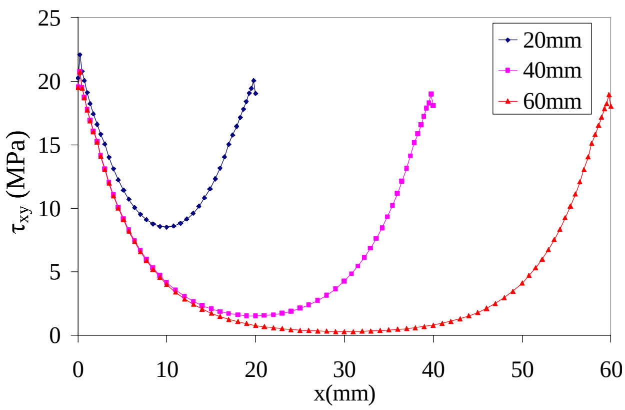

Fig. 8: Effect of joint length on initial shear stress

The general trend is that the shear stress distribution is approximately equal between examined overlap lengths towards the ends of the overlap. There is a reduction shear stress at the centre of the overlap as its length is increased.

6 Prediction of creep using FEA

Using the finite element modeling technique discussed, the creep of the overlap region has been predicted for variation in adherend thickness under constant force. Joint loadings of 166MPa and 116MPa have been used for the 14-ply and 20-ply joints respectively. Creep of the entire double strap joint will be equal to twice this value. The effect of adherend viscoelasticity has been neglected. Three measurement techniques have been used. The first is the relative displacement between the adherends at the centre of the overlap region (1). The second is the relative displacement between adherends at the end of the overlap region closest to the joint centreline (2). The third is the relative displacement between the top and bottom adherends at points attached to the external panel (3). All measurements are taken at the interface between the laminate and adhesive as shown in Fig. 9. The first and second methods were used to confirm whether it is valid to conclude that the total creep of the adhesive is the same at the ends of the overlap region as it is in the centre. The third method was intended as an evaluation of the total overlap region creep.

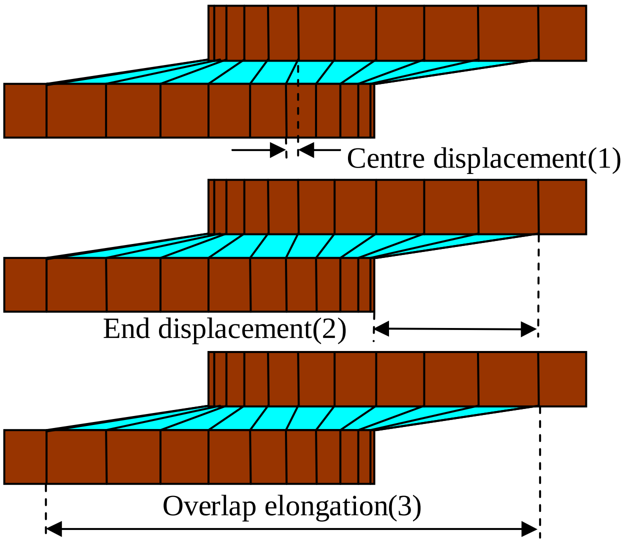

Fig. 9: Creep measurement of overlap.

A number of observations can be made from the results, which must be taken into account when designing a creep resistant joint. Results presented have been confined to the displacement upon unloading after ten load cycles.

Consideration is first given to the final relative displacement at the centre of the overlap. It has been shown in Fig. 10 and Fig. 11 that under a given applied panel force, a difference in level of displacement can be predicted at the centre of an overlap upon unloading, with variation in adherend thickness. The displacement of the 20-ply overlap end was found to be marginally higher. This is consistent with the observation in Fig. 7 that with an increase in thickness, there is a larger shear stress present at the centre of the overlap region. This point cannot be considered as the sole factor in the prediction of joint elongation, as further results will reveal. For the case examined, the difference in stiffness is considered to be within the same order of magnitude, leading to a small difference. This is indicative of general trend, and the difference is expected to increase with difference in joint stiffness.

The relative displacement between the top and bottom adherends at the end of the overlap region closest to the centerline shows a trend similar to the total elongation (Fig. 10 and Fig. 11). However, the displacement values are slightly less. Therefore, the creep has not only been affected by the shear strain present in the adhesive, but there has also been an elongation of the adherends. The elongation of the adherends is the result of yielding in the adhesive during loading, and the equilibrium established between the adherends and adhesive as the adherends attempt to move back to their original positions upon unloading.

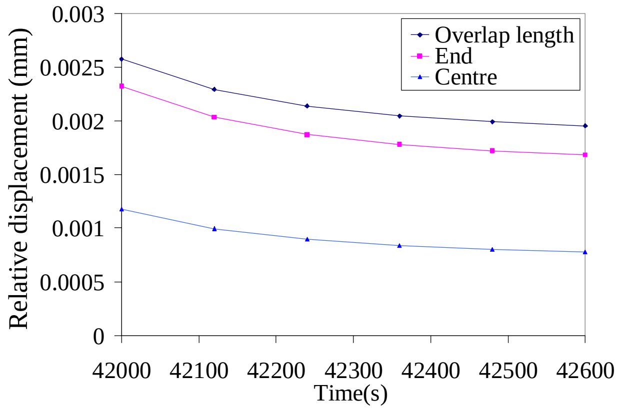

Fig. 10: 14-ply creep results at unload after ten load cycles

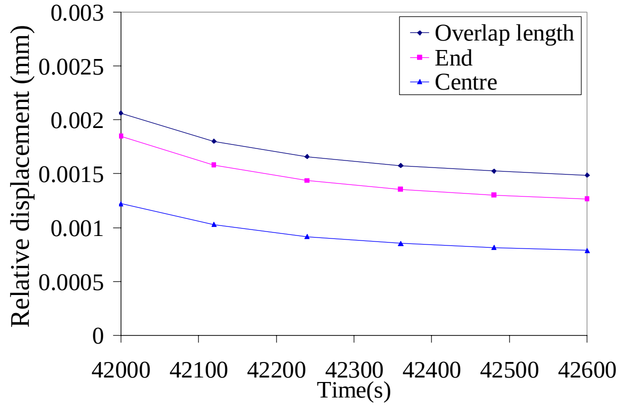

Fig. 11: 20-ply creep results at unload after ten load cycles

Examination of the total overlap region elongation has revealed that the stiffer joint actually has a lower final displacement, even though the centre has a marginally higher level of creep. Therefore, there is some ambiguity in stating that the total creep of a joint will be dependent on the stress levels in a particular region.

7 Evolution of shear stress

Under the condition of cyclic loading, the shear stress in the centre of the overlap region has been found to increase over time, and with load cycle number. This effect is displayed in Fig. 12. The main factor identified for this evolution is the gradually diminished load carrying capacity at the ends of the overlap, which can be seen in Fig. 13 and Fig. 14 through reduced shear stress towards the extremes at later load cycles. When this occurs, the load applied to the joint must be balanced out through increased shear in the centre of the overlap. At the shear peaks the total strains can be found to increase with number of load cycles, however, the maximum stress is reduced. Cyclic load application causes incremental plastic deformation, along with creep. The load is therefore redistributed towards the centre of the overlap.

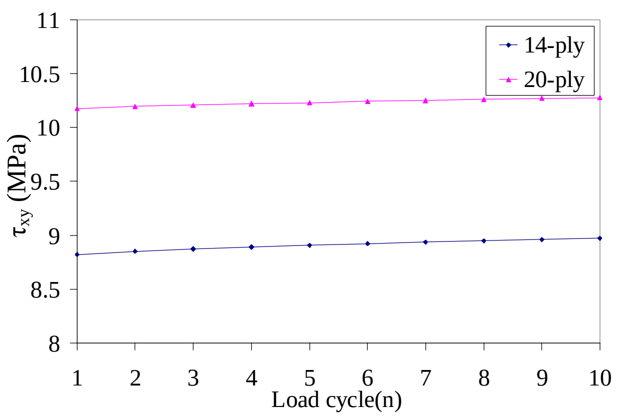

Fig. 12: Evolution shear stress at overlap centre.

The significance of the considerations of loads as cyclic has been established. The central shear stress has been shown to increase over time in Fig. 12. The significance of loading history can also be seen, as the changes appear to decrease with time, allowing the possibility that the central shear stress may plateau, or reach a value when the increment between load cycles is inconsequential.

The increment in the shear stress with respect to load cycle at the centre of the overlap has been shown to be slightly larger in the case of the 20-ply overlap compared to the 14-ply overlap.

8 Mechanisms for the reversal of creep

Two returning mechanisms are identified to exist within a joint. The first is one common to all polymer materials, which has been well documented and is related to viscoelasticity. The second is a reversal mechanism found within joints, and is related to the adherend deformation.

8.1 Polymer viscoelasticity

Most polymers exhibit what is termed viscoelastic behaviour. This means that under the condition of sustained loading there will be an initial elastic deformation, followed by a time dependent deformation. This time dependent deformation is caused by the gradual stretching out of polymer chains. When the loading is released, the polymer chains have a tendency to move back towards their original positions[6]. The extent to which they do move back is dependent on the specific polymer. Therefore, what can be termed as creep is not always permanent when considering polymer materials. It follows that the joint will have a tendency to move towards its original position when unloaded, which is caused by the recoiling of polymer chains.

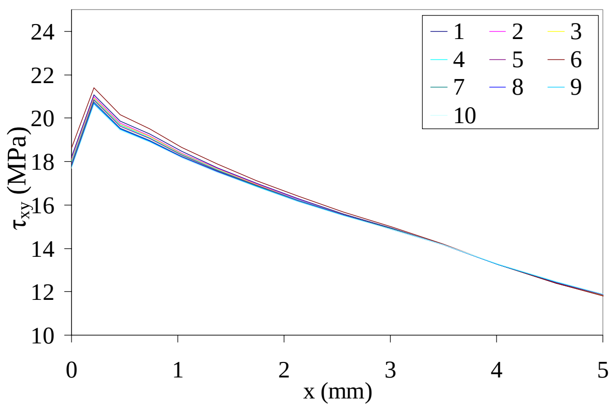

Fig. 13: Evolution of shear peak - 14-ply.

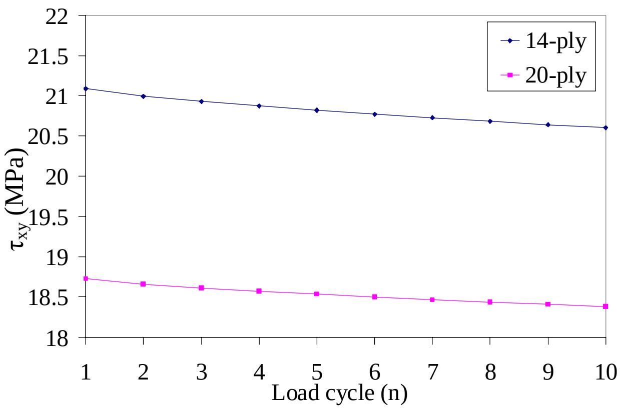

Fig. 14: Evolution of peak shear stress.

8.2 Creep reversal mechanism in joint

The central adherend attached to the external panel at the extremes of the overlap has been identified as the area under the highest direct stress. When the joint is loaded, the adhesive directly adjacent to this region will undergo the highest level of deformation found to occur in the joint. The adjacent adherend is not yet loaded, thus has zero extension. This results in the adhesive being placed into shear. Because the level of shear stress and strain is high at this point, the adhesive undergoes plastic deformation, and higher levels of creep than those found further towards the joint centre.

If the viscoelastically deformed adhesive was now unloaded without the presence of the adherend, a new unstressed shape would result. However, when the loading is removed from a joint, the adherends attempt to return to their initial length, altering the loading condition on the adhesive. Since the adhesive is attached to the adherend, when the loading is removed from the joint the material in the ends of the overlap is actually placed into shear in the direction opposite to that found in the loaded condition. This shear direction will be referred to as negative. This results in adhesive creep in the opposite direction to that found in the loaded condition, thus a mechanism for reversed creep.

The effect of creep reversal is reduced if the adherend undergoes permanent creep in the loaded condition. It must also be noted that the creep reversal is confined to the extremes of the overlap. Since the adhesive is placed into a negative shear stress according to the convention used in this paper, equilibrium requires that the centre of the overlap balance the force through a positive shear stress, which is shown in Fig. 15. With increased adherend stiffness, the mechanism for reversed creep increases in effectiveness, however, there is reduced need since the adhesive strain levels in the ends of the overlap are not as high as in the more flexible adherend case. Therefore a case by case approach is required for determining the effectiveness of creep reversal. The magnitude of the negative shear can be seen to reduce over the unload period in Fig. 15. This is due to the adhesive supplying less resistance to the adherends as it moves towards its initial shape.

The effect of the creep reversal mechanism can be seen in Fig. 16 at one of the shear stress peaks of the joint. When the joint is unloaded, the shear peak is actually placed into negative shear. This then results in a reduction in the total strain over the unload. Total strain is the summation of the elastic, viscoelastic, and plastic strain components. As the total strain is reduced, the magnitude of the negative shear stress is also reduced, as indicated through the diagonal lines moving towards the top left in the negative shear stress region of the graph. Therefore, the reversal mechanism is most effective when the joint is first unloaded.

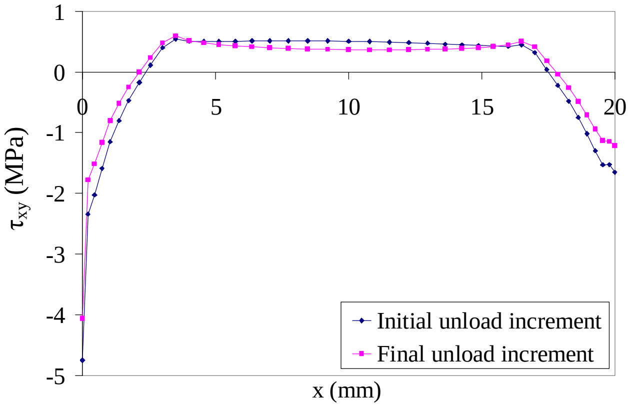

Fig. 15: Unloaded 14-ply shear stress distribution.

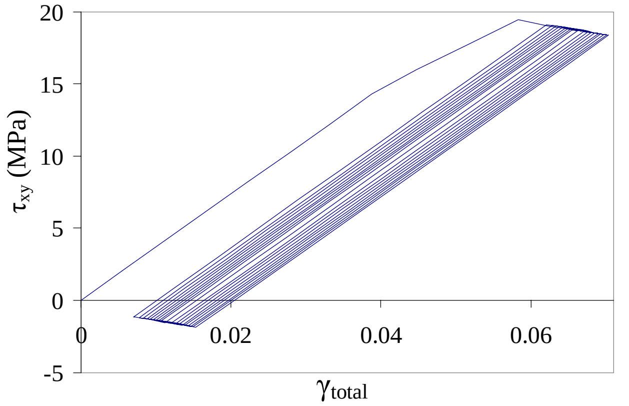

Fig. 16: Creep reversal mechanism at shear peak.

As further load cycles are applied to the joint, the magnitude of the shear stress at the peaks upon loading is reduced, and the total strain is increased due to diminished load carrying capacity, as discussed previously. This leads to larger magnitudes of negative shear upon unloading, hence marginally faster creep reversal. The effect of creep in the loaded condition still outweighs the effect of the reversal mechanisms, which can be seen in Fig. 16 through a gradual increase in total strain. The joint overlap length also increases (Fig. 10 and Fig. 11).

9 Discussion on creep mechanisms

The contributions of the adhesive and adherend to creep will now be discussed. Before this can proceed, it must be outlined that the loading history of the joint is very important, particularly when moving from a joint that has had no previous loading, to one that has completed its first load cycle. From this time, every successive loading on a joint which is subject to cyclic loading conditions will result in a redistribution of load.

9.1 Adhesive layer creep:

The adhesive is loaded primarily in shear. This results in the displacement of adherends relative to one another. Very little direct stress is transferred through the adhesive due to its relative flexibility compared to the adherend. Displacement continuity at the centre of the overlap region provides a starting point for examining the creep. Any creep experienced by the adhesive due to the central shear stress level will translate to a net displacement across the entire overlap. This is due to the overlap centre having the lowest shear stress. Also note that the central shear stress being the lowest expected value within the joint is a result confined to the case of a balanced joint. The shear stress in the centre of the overlap affects the time dependent elongation of the whole joint, however, it is not the sole influence on joint creep.

The peak shear stress found at the overlap extremes has been observed to reduce in magnitude over a sustained loading. This results in the stress at the overlap centre being raised as the load is balanced out across the overlap. The reason for this redistribution of load is the loss of load carrying capacity in the ends of the overlap as they creep and undergo plastic deformation. The level of shear stress in the overlap centre has also been found to increase with subsequent loadings under conditions of cyclic load. The cumulative effect of plastic deformation and creep is responsible for this behaviour.

9.2 Adherend creep

Adherends are the primary load path of the joint, with the adhesive acting as a means to pass the loading in a perpendicular direction. Thus, the main loading found is a direct stress. Therefore the adherend can also be expected to creep. The primary location for creep elongation is at the extremes of the joint, within the central adherend. At this point, the direct stress is largest and equal to the panel stress. A more flexible adherend will promote this type of creep.

When the joint is loaded, the adhesive at the extremes of the joint will have the highest levels of permanent deformation. When the load is removed from the joint, a new equilibrium must be established as a result of the new shape of the adhesive. The adhesive is now loaded in a direction opposite to that observed during loading. The adherend is placed into tension, hence a tensile strain results. This translates to an extension of the joint, which adds to the observed creep. This effect is confined to areas away from the centre of the overlap.

With an increase in the adherend stiffness, less extension of the external panel will occur under a given loading. This translates into the ends of the overlap, resulting in lower shear stresses in the adhesive towards the joint extremes (Fig. 5). This is because the adhesive is attached to the adherend, and hence must have an equal extension at the interface. Equilibrium requires that the total load applied to the joint be taken up in the form of a shear force by the adhesive. Therefore, since the load is lower at the ends of the overlap, the centre of the joint is now under a higher shear stress. The converse is also true. If the adherend stiffness is reduced, the shear in the ends of the overlap is increased due to higher adherend extension, and the shear stress in the centre of the overlap is decreased. The implication of this is that an adherend of greater stiffness will result in a higher level of creep at the centre of the overlap.

In summary, the stress in adhesive at centre of the overlap affects creep of entire joint, whereas regions located away from the centre require the establishment of a force balance between the adhesive and adherends upon unloading, result in adherends being put into tensile strain. Permanent adhesive deformation affects the redistribution of stresses within the joint, and the migration of shear stress towards the centre of the overlap. Adherends may also undergo creep resulting in joint elongation. With variation of adherend stiffness, a change in the shear stress distribution results, hence altering levels of both adherend and adhesive creep.

10 Load path analysis

Load paths through the joint have been plotted in Fig. 17. These plots are contours parallel to the total stress vector V_x from Eq.2 [7] derived from the finite element analysis. The contours define regions that transfer a constant resultant force in the x-direction and therefore represent the transfer of load through the joint as described in [8].

$$\begin{aligned} V_x &= \sigma_{xx} i + \tau_{yx} j + \tau_{zx} k \\ V_y &= \tau_{xy} i + \sigma_{yy} j + \tau_{zy} k \\ V_z &= \tau_{xz} i + \tau_{yz} j + \sigma_{zz} k \end{aligned} \tag{2}$$

The plot in Fig. 17(a) shows the transfer of load across the bond line in the loaded joint. The contours in Fig. 17(b) indicate the participation of the adherends in the restoring forces that reverse the creep at the ends of the joint. The load path upon unloading also appears to be asymmetric. This is consistent with the observation in Fig. 15 that there is a shear stress of larger negative magnitude on one side of the joint than the other. In this case, the left hand side of the overlap depicted in Fig. 17. Note that these plots were generated from a finite element analysis where the joint was completely unloaded after the sustained loading. Thus, there is no observed load path moving out of the joint in Fig. 17(b).

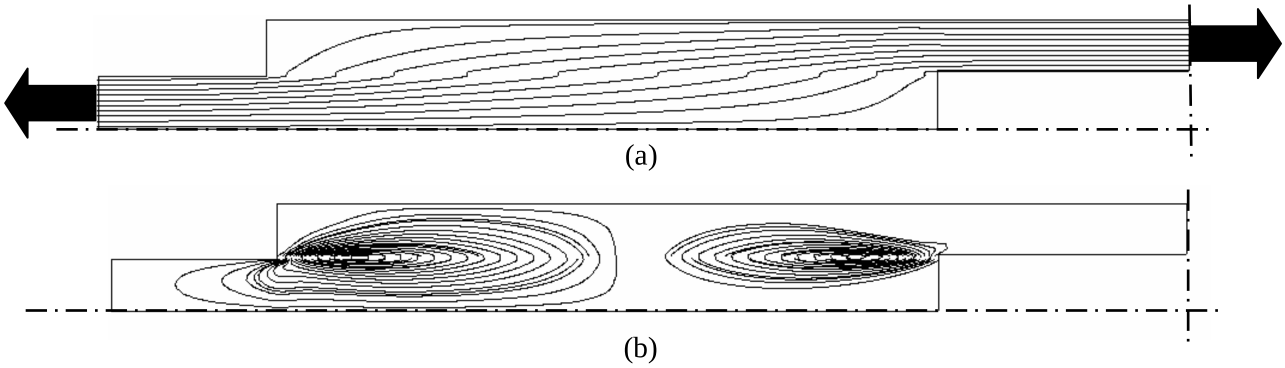

Fig. 17: Load path in quarter of joint; (a) Loaded; (b) Unloaded.

11 Conclusion

The mechanisms for creep have been discussed, along with the effect of joint geometry for the case of a double strap joint. It has been found that for a given force, an increase in overlap length will result in a lower central shear stress in the adhesive layer, with very little effect on the distribution at the ends of the overlap region. An increase in adherend stiffness, influenced by either thickness or material properties, will result in a lowering of the shear stress found at shear peaks, and raising of the stress found in the overlap centre.

Two main features of a joint are identified as having significance with regard to creep recovery upon unloading. The first is the viscoelasticity of the polymer, and the second is the effect of adherend stiffness on the reversal of creep. The adherends are identified as being responsible for an observed shear stress reversal in the ends of the joint upon unloading, which occurs as a result of an equilibrium being established between the deformed adhesive and the stiff adherend. This leads to creep in the direction opposite to that observed during loading. In later load cycles, the magnitude of the reversed shear stress upon unloading is larger, resulting in faster creep reversal. However, the net effect of cyclic loading is still an increase in joint length.

Prediction of creep must take the geometry of the entire joint into consideration, as simply designing according to the centre shear stress of the adhesive may result in vital creep recovery provided by the adherends being neglected.

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13 References

[1] L. J. Hart-Smith, Engineered Materials Handbook, in: T. J. Reinhart (Ed.) vol 1, Composites, ASM International, Metal Park, Ohio, US, 1987, pp. 479-495.
[2] L. J. Hart-Smith, Composites 25 (1994) 895-898.
[3] M. C. Y. Niu, Composite Airframe Structures, Conmilit Press, 1992.
[4] T. Chen, NASA Report TM-2000-210123, ARL-TR-2206 (May 2000).
[5] MSC.Marc users manual, 2005.
[6] M. T. Shaw, W. J. MacKnight, Introduction to Polymer Viscoelasticity, Wiley, 2005.
[7] P. E. Lewis, J. P. Ward, Vector Analysis for Engineers and Scientists, Addison-Wesley, New York, 1989.
[8] D. W. Kelly, P. Hsu, M. Assadullah, Engineering Computations 18 (2001) 304-313.