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Effects of interface and tensile properties in the dynamic fracture of layered structures

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Abstract

Finite element modeling of crack extension under impact was performed to study the suitability of layered composite structures in plasma-facing and primary wall structures for ITER and other fusion devices. The layers may consist of dissimilar metal alloys, each of which performs a necessary design function for sputtering resistance, heat removal, and structural integrity. Several layered structures with varying material properties were modelled using finite element analysis. Compared to monolithic solid bars with the same mechanical properties, layered structures with frictional interfaces dissipate more energy before a pre-crack normal to the interface can propagate. For these layered structures, there is an optimum for the coefficient of friction that provides maximum resistance to crack extension.

1. Introduction

Layered composite structures have been selected for a variety of plasma facing and first wall applications in ITER and other fusion devices. These layered structures will be used for components, including the primary wall, the limiters and the divertor, that will experience severe service conditions. The methods for bonding the layers in these structures and their performance under a variety of mechanical and thermal loading conditions has been the topic of several recent and ongoing studies by the ITER partners [1–5].

While there have been substantial efforts to investigate these structures to establish the strength and integrity of the bond, little attention has been paid to dynamic fracture issues within such structures. Dynamic loading is often used as a method of assessing lower bound fracture resistance since dynamic fracture usually tends to result in less energy absorption than standard fracture toughness tests performed at more moderate strain rates. In fact, there has been very little consideration of dynamic fracture of laminate structures other than some early considerations regarding potential strengthening and fracture resistance [6]. Other works deal with interfacial crack initiation and mixed mode cracking [7–10]. The current work examines the dynamic loading effects in layered structures when mechanical and interfacial properties of the layers are varied.

2. Modeling and computational approach

All modeling was performed using a dynamic finite element code, ABAQUS Explicit, from Hibbit, Karlsson & Sorensen [11]. Some portions of the input files were generated using IDEAS-SDRC Version VI [12]. A dynamic analysis procedure which implements an explicit integration rule is used by the ABAQUS explicit code [11]. Using the central difference integration rule, the code integrates through time using many small, stable time increments. No user intervention is required within the time increment process; it is fully automatic. The code calculates the time increment necessary by identifying the smallest element in the mesh and an internal stability limit. With the time increment determined, the solution can be determined without iteration or tangent

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stiffness matrices. Thus, contact and surface interactions are simplified.

The existing ABAQUS elastic–plastic material model was modified to model crack extension. Normally, ABAQUS treats crack extension by calculating an element-averaged strain (ε^{pl}) and then deleting elements in the mesh when any element reaches an input defined plastic fracture strain (ε_f^{pl}). In order for this deletion of elements to produce stable results, the stress state of the damaged element must be reduced to zero by the time of fracture. ABAQUS accomplishes this by applying a damage level parameter to the material prior to fracture. This damage parameter is used to degrade the stress state as well as the elastic moduli. The damage value of any element is zero until the strain in the element exceeds a user-defined offset fracture strain (ε_0^{pl}). The damage (D) in an element can range from zero (no damage) to one (failed) and is calculated from the equivalent plastic strain as follows:

$$D = \frac{\left[\varepsilon^{pl} - \varepsilon_0^{pl}\right]}{\left[\varepsilon_f^{pl} - \varepsilon_0^{pl}\right]}.$$

When the damage reaches a value of one, the element is deleted from the mesh and a crack is formed or extended.

A user-defined FORTRAN subroutine has been written to modify the above mentioned model [13]. This subroutine is called by ABAQUS instead of the ABAQUS material fracture model and uses the same mechanism for modeling crack initiation and extension as the ABAQUS model with the exception of when the damage (D) is incremented. A hydrostatic stress, averaged over the three principal stresses in the element, is used to determine if an element is under tensile or compressive loading. If the hydrostatic stress is tensile, D is allowed to increase in that time increment. Otherwise, no further damage can result.

The finite element model used is a simulation of a drop tower Charpy impact test. The two-dimensional specimen (1 cm × 5.4 cm) is made up of quadrilateral solid (continuum) elements (4 node bi-linear, reduced integration with hourglass control) and modelled in half-symmetry (see Fig. 1). The geometric model contains a sharp pre-crack at the bottom of the specimen to a depth of 0.25 cm (one-quarter of the specimens overall thickness) at the mid-length. The pre-crack provides a direct indication of the energy to extend the crack without the influence from crack initiation. In order to determine the relative fracture resistance of multi-layered structures, the amount of energy required to extend the pre-crack by 0.025 cm (the smallest mesh size used) is compared for all cases investigated. This small crack growth was considered as the onset of further crack propagation and eventual fracture of the structure.

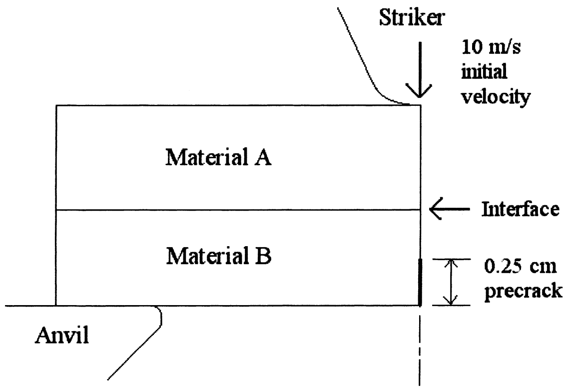

Fig. 1. Charpy impact test geometry

3. Layer configuration and material properties

Two types of specimens were investigated. These included solid bar structures and bi-layered structures. Two types of interfaces were assumed for the bi-layered structures: Either the layers were 'tied' together (rigidly bonded) or they interacted via frictional forces. In the former case, no direct energy was dissipated due to adhesion between the layers, while in the latter case, substantial energy could be dissipated in the form of frictional sliding.

The material properties for these studies represent a wide variety of stainless steels which have been used successfully in finite element modeling (FEM) and mechanical properties test programs [3–5]. Using the values shown in Table 1, a bi-linear stress–strain material model is applied to the solid elements. All of the material models are considered to have the same elastic moduli.

A single material code or a combination of material codes (represented with a plus sign or a slash joining the codes together) represents each structure. Single material code structures represent a solid bar made of the corresponding material. Structures with two material codes joined with a plus sign represent a bi-layered structure with a frictional interface (coefficient of friction equal to one). The top layer has the material properties given by the first material code listed and the bottom pre-cracked layer has the material properties given by the second material code. Structures with two material codes joined with a slash represent a bi-layered structure with a 'tied' or rigidly bonded interface. As before, the first material code represents the properties of the top layer while the second represents the properties of the bottom layer which is 0.5 cm wide and is pre-cracked to a depth of 0.25 cm. The length of the layers is 5.4 cm and the total width including top and bottom layers is 1 cm.

All of the computations are performed for plane strain conditions. A striker of mass 10 kg and an initial

Table 1
Material properties used to model stainless steels in this study

Material code	Yield stress (MPa)	Hardening modulus (GPa)	Offset fracture strain	Fracture strain
1C	300	1.333	0.200	0.250
2C	300	1.333	0.400	0.500
1Y	450	1.333	0.200	0.250
1H	300	2.666	0.200	0.250

velocity of 10 m/s (kinetic energy of 500 J) impacts the layered structure from the top. Energies absorbed by the specimen during the extension of the pre-crack by 0.025 cm are used to compare the relative superiority of various layered structures.

4. Results and discussion

4.1. Mechanical properties

The total energy in deformation and fracture is the sum of two dominant components, the strain energy and the friction energy. Each of these energy components are computed per element and summed to produce the total strain energy and total friction energy within the model. It is important to note that the values of the strain energies and the frictional energies are of similar order, both playing significant roles in the total energy absorption (except when the interfaces are frictionless).

Figs. 2 and 4 show the total energy absorbed during the extension of a pre-crack by 0.025 cm in several different structures. The control solid bar specimen (1C) shown on the left hand side in Fig. 2 absorbs approximately 4.11 J of energy in extending the pre-crack by 0.025 cm. A solid bar specimen with a higher yield strength (1Y) dissipates 5.42 J. Tied bi-layered structures (material codes joined with a slash) perform slightly better than the 1C structure absorbing 4.93 J when the bottom layer has a higher yield strength. When the bottom layer has a higher yield strength, the energy dissipated in extending the pre-crack 0.025 cm falls to 4.77 J.

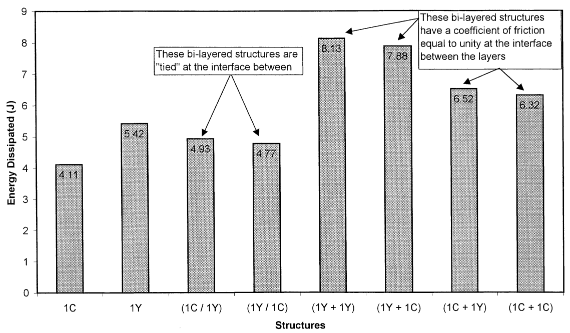

Fig. 2. Effect of yield strength on the total energy dissipated to extend a crack by 0.025 cm.

When the interface between the top and bottom layers has a coefficient of friction equal to unity, bi-layered structures outperform the tied and solid structures. The bi-layered structure dissipates 7.88 J when the top layer has a higher yield strength of 450 MPa (1Y+1C). If we use the higher yield strength material in the bottom layer instead, then the energy dissipated in extending the pre-crack by 0.025 cm is 6.52 J (1C+1Y). As a comparison, the same structure with a lower yield strength of 300 MPa in both layers dissipates 6.32 J. When both layers have the higher yield strength of 450 MPa the energy dissipated is 8.13 J.

It is important to note that the energy dissipated is higher in the 'tied' case when the bottom layer has a higher yield strength. However, in the case of a frictional interface, higher energy is dissipated with the top layer having a higher yield strength. This anomaly is due to the fact that the energy dissipated due to an increased deformation in the top layer more than compensates for the lower energy required to extend the crack in the bottom layer with the lower yield strength.

As can be seen from Fig. 2, bi-layered structures with frictional interfaces outperform their solid counterparts. By introducing a frictional interface, the energy dissipated in extending a crack by 0.025 cm increases from 4.11 J in a solid specimen to 6.32 J in a bi-layered structure with a frictional interface. This interface serves to dissipate some of the energy in friction instead of plastically deforming the material. Thus, the bi-layered structure during impact performs in a superior fashion compared to conventional structures.

The effect of fracture strain is illustrated in Fig. 3. The solid bar structure with 1C properties dissipated a total energy of 4.11 J. When the fracture strain was doubled (as was the offset fracture strain), the structure (2C) dissipated 10.7 J in extending a crack 0.025 cm. Thus, a 160% increase in energy dissipated is realized in solid structures. Bi-layered structures with frictional interfaces perform in a likewise manner. When the layers had low fracture strain (1C), the structure dissipated a total of 6.32 J. With twice the fracture strain (2C), the bi-layered structure dissipated a total of 16.72 J in contrast to 10.70 J for the single layered solid bar like structure.

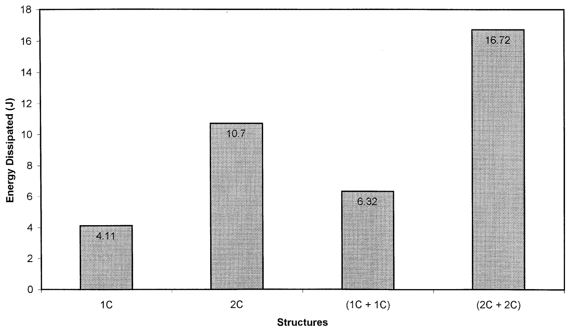

Fig. 3. Effect of the fracture strain on the total energy dissipated to extend a crack by 0.025 cm.

Fig. 4 depicts the findings when the effect of hardening modulus is considered. Increasing the hardening modulus in a solid bar specimen by 100% (which is approximately a 33% increase in the area under the stress–strain curve), results in an increase in energy dissipated from 4.11 J in the 1C case to 5.84 J in the 1H case, a 42% increase. Bi-layered structures with frictional interfaces responded better than the solid structure to an increase in the hardening modulus in either of the layers. Increasing the hardening modulus in the top layer from 1.333 to 2.666 GPa resulted in a total energy dissipated of 8.12 J. Increasing the hardening modulus of the bottom layer in the same manner resulted in a total energy dissipated of 8.30 J. Thus, in bi-layered structures with frictional interfaces, an increase in hardening modulus of either layer (only half the structure) results in a 30% increase in energy dissipated when compared to a structure with 1C material properties in both layers.

4.2. Interface properties

The properties of the interface play an important role in bi-layered structures. Structures with a 'tied' interface exhibit characteristics of solid bars. Structures with friction at the interface dissipate additional energy through the friction between surfaces instead of just in bending.

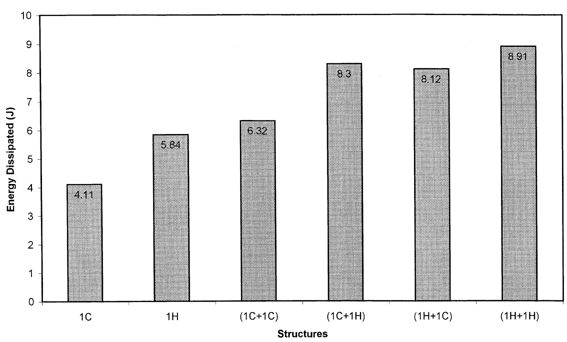

Fig. 4. Effect of hardening modulus on the total energy dissipated to extend a crack by 0.025 cm.

Fig. 5 provides an illustration of the distribution of energy dissipated in similar bi-layered structures when the coefficient of friction varies. The coefficient of friction is varied from 0.25 to 5.0. Typical coefficient of friction values for metal on metal range from 0.1 to 3.0 with even higher values possible if the interface is saw-toothed [14]. All of these bi-layered structures have material properties of 1C in both layers with a 0.25 cm pre-crack in the bottom layer.

As can be seen from Fig. 5, the strain energy decreases slightly as the coefficient of friction increases. The frictional energy dissipated, on the other hand, increases rapidly as the coefficient of friction increases from 0.25 to 2.00. The strain energy term dominates the frictional energy term until the coefficient of friction rises to two. Any coefficient of friction above two results in the strain energy term being less than the frictional energy dissipated. However, above a coefficient of friction of two, the energy dissipated in friction begins to experience a diminishing return when the coefficient of friction is increased.

5. Conclusions

The following conclusions were made regarding the effects of mechanical and interface properties in the investigated structures under simulated impact loading. All comparisons are based on increases in the area under the stress–strain curve due to the corresponding changes in the yield strength, hardening modulus or the fracture strain. By choosing materials that exhibit these properties, impact resistance of layered structures (such as the before mentioned ITER primary wall) can be increased.

1. Bi-layered structures with a frictional interface are superior to solid or 'tied' structures. For bi-layered structures with dissimilar yield strengths in the top and bottom layers, the structure with a higher yield strength in the top layer performs better.

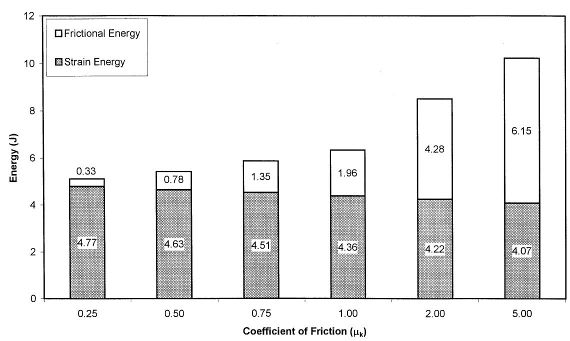

Fig. 5. Distribution of energy dissipated to extend a crack by 0.025 cm in bi-layered structures with varying coefficients of friction at the interface between layers.

2. The total energy dissipated to extend a crack increases disproportionately as the coefficient of friction increases. However, the energy dissipated in friction begins to experience diminishing returns above a coefficient of friction of 2.0.
3. Increasing the fracture strain results in a proportional increase in the energy dissipated to extend a crack for both solid and bi-layered structures.
4. An increase of the hardening modulus in a solid bar or bi-layered structure results in a disproportionate increase in the energy dissipated to extend a crack. In bi-layered structures the relative increase in energy is much higher than in the solid bar case.

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