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D. Hughes, C. Ruiz, I. Martindale. Application of high-strain-rate material testing to the study of soft-body impact. *Journal de Physique IV Proceedings*, 1994, 04 (C8), pp.C8-565-C8-570. 10.1051/jp4:1994888 . jpa-00253449

HAL Id: jpa-00253449

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Submitted on 4 Feb 2008

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Application of high-strain-rate material testing to the study of soft-body impact

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Abstract

The design of titanium fan blades exposed to soft body impact relies on the mathematical modelling of the structural response for which a knowledge of the material is necessary. The difficulties of producing an accurate constitutive relation for a high strength titanium alloy are described. It is shown that a very simple constitutive relation is adequate for modelling the early stages of the impact response. This is found to be sufficient for the purpose of design since catastrophic failure as opposed to large scale deformation occurs shortly after impact.

1.0. INTRODUCTION

The impact of soft bodies on titanium alloy fan blades has been studied at Oxford for several years. Experiments simulating this event have been carried out in conjunction with finite element studies using DYNA3D. This code is particularly well suited to modelling large, plastic deformation caused by impact loading. A wide range of strain rates is encountered during the course of this event so it is important that a constitutive relation be used in the code which can accurately describe the material behaviour.

2.0. THE USE OF A CONSTITUTIVE RELATION FOR TITANIUM ALLOY

2.1. Obtaining the material data

Tensile tests at quasi-static, intermediate and high rates of strain were performed using cylindrical specimens cut from titanium alloy Ti-6Al-4V. The stress-strain curves obtained are shown in figure 1. The quasi-static tests showed a modest amount of work-hardening after yield up to a strain of about 8%, beyond which the strength, gradually dropped. At an intermediate strain rate of there was an increase in yield strength, no work hardening and a gradual reduction in strength beyond 5% strain. The behaviour at impact rates was very similar to that at the intermediate rate except that the strength fell away shortly after yield.

2.2. Interpretation of test data

The experimental data clearly shows a difference in the mechanical properties. This phenomenon must be considered in any analytical work. Various constitutive relations have been used to model the material response under impact conditions. In the constitutive equation by Cowper and Symonds [1], later published by Ting and Symonds [2], the static yield stress is related to an effective yield stress at a non-

zero plastic strain rate by the introduction of material dependent empirical constants. Further developments proposed by Johnson and Cook [3], who made allowances for thermal softening and Zerilli and Armstrong [4] who used dislocation processes to describe the plastic flow for different material types.

Clearly, there exists a number of different types of constitutive equation with increasing complexity and number of empirical constants to be evaluated.

Ideally, materials testing will give curves of true stress against true strain over a range of strain rates and at a number of different, constant temperatures. However, the real situation is somewhat different. In all these tests one measures force and displacement which are simply related to true stress and strain only whilst deformation is uniform. Once necking starts true strain is no longer a function of overall extension and the simple uni-axial stress state is replaced by a complex tri-axial one. Localization occurred at low strains with this alloy because it exhibited very little, if any, work hardening. Necking will occur earliest in the high strain rate tests because of local heating effects. Therefore, the test of greatest relevance to the numerical modelling of an impact event is likely to contain the largest inaccuracies. The early onset of necking was confirmed by high speed photography which indicated the development of a neck at a nominal strain of less than 8 %.

A further assumption is that temperature remains unchanged throughout the tensile test. Whilst this may be true at low and medium rates the same cannot be said for high rate tests where there is insufficient time for the substantial quantities of heat generated to be conducted away from the zone of plastic deformation. Investigations on remco iron have shown temperature rises immediately after failure of 250-300°C in the region of the neck where strains of between 2 and 3, based on the reduction in area, had occurred [5]. Although comparable strains were lower in the case of the titanium alloy considered here (0.43 - 0.72) its greater strength and lower coefficient of thermal conductivity favours early and more pronounced localization. Titanium's lack of ductility prevented the reduction in area at failure equalling that for iron. Nevertheless temperature rises of several hundreds of degrees could have occurred.

The final point to consider is the extent to which the initial geometry of the specimen affects its measured response. By choosing a cylindrical shape one hopes to maintain a uni-axial stress state that is simple to analyze. However, it may be necessary to find the properties of a material in its as manufactured state in which case the shape of the component may restrict the choice of specimen geometry. In order to produce specimens from thin plate it was necessary to use the strip geometry depicted in figure 2. It was also necessary to use both long and short gauge length variants, nevertheless, the dimensions of the cross-section (6 mm x 1 mm) were kept the same.

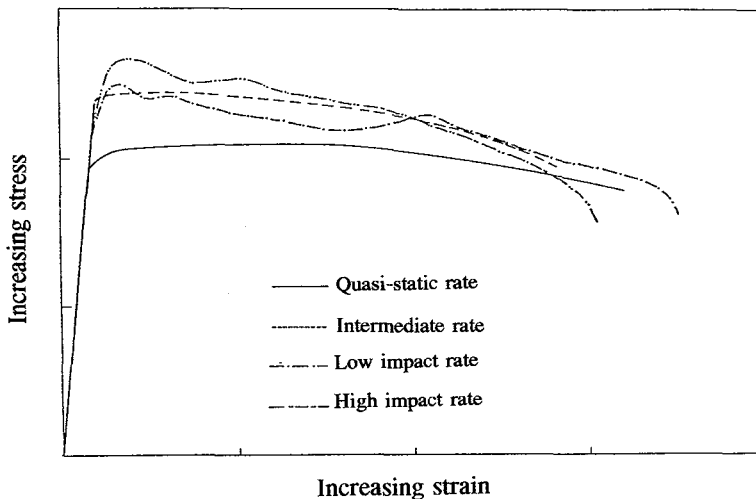


Figure 1. Nominal stress-strain curves of Ti-6Al-4V at increasing strain rates

Figure 3 compares the results of high strain rate testing for the 3 different specimen geometries. Each curve is an average of 3 or more test results. Both types of strip specimen show higher yield stresses and fail earlier than their cylindrical counterparts. Note that the cylindrical specimens were tested at a lower impact rate whilst the long and short strip specimens were tested at mean rates of 350 and 1550s^{-1} higher than the cylindrical tests. Earlier work with the cylindrical geometry suggests that such differences in strain rate will only have a small effect. Micrographs of different regions of the plate showed no significant variations in structure. Thus, it would appear that the difference in geometry is causing this change in apparent behaviour. This is not unexpected. The fact that titanium exhibits little or no work hardening coupled with its relatively high strength and moderate thermal conductivity mean that necking will tend to start early and hence the majority of the observed behaviour will be dominated by the way in which plastic flow develops. Obviously, the slimmness of the strip geometry limits plastic flow. To conclude, it is apparent that the tensile test does not provide true stress-strain data for this alloy, making the formulation of a highly accurate constitutive relation very difficult. Nevertheless, from a designers point of view a constitutive equation must be chosen based on the available data in order that a component can be designed to withstand a typical impact situation. Therefore, we can illustrate this process whereby a relatively simple constitutive equation can be used in a complex impact situation.

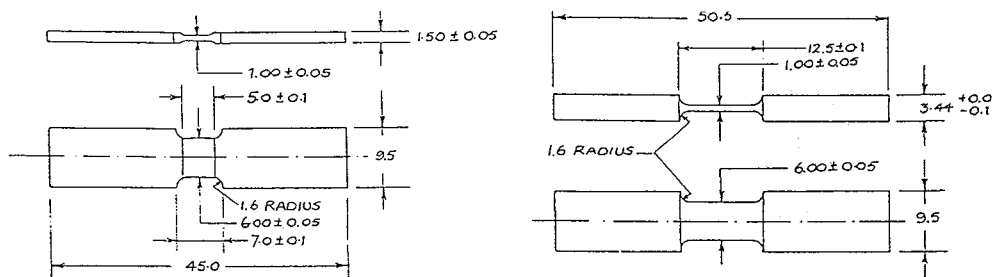


Figure 2. Design of tensile strip specimen

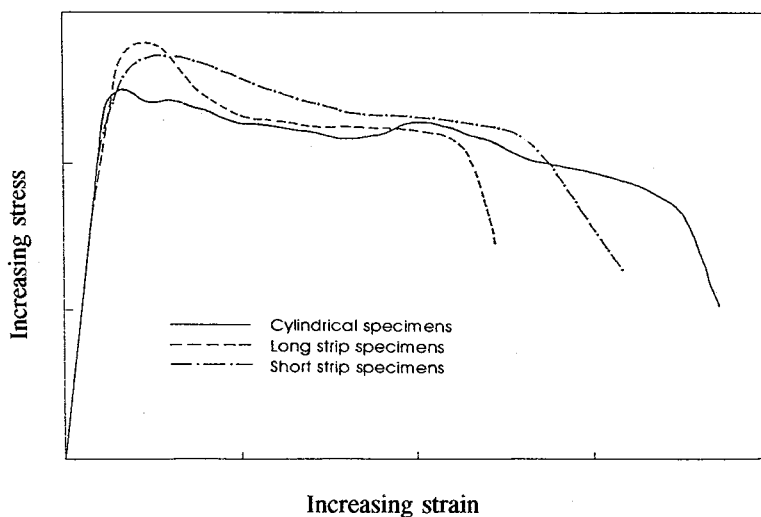


Figure 3. Comparison of stress strain behaviour for different specimen geometries

3.0. AN ILLUSTRATION OF A SIMPLE CONSTITUTIVE RELATION APPLICATION

3.1. Introduction

The problem was to determine the critical impact velocity to cause a transition from Mode A failure (large plastic deformation) to Mode B failure (leading edge tearing) for a range of different fan blade leading edge profiles under soft body impact.

A combination of experimental testing and mathematical modelling was used to define the failure as outlined below.

3.2. Experimental programme

Soft body impact tests were performed using a high powered gas gun facility. Six different types of specimen were machined from titanium alloy Ti-6Al-4V plate. Each profile consisted of two components, the leading edge thickness or L.E.T. (radius) and the length of chamfer. Figure 4 shows the geometrical parameters of the profiles and table 1 indicates the differences between the profile types.

The projectiles used to simulate the soft body impact of a birdstrike were cylindrical in shape and manufactured from a mixture of gelatine and water. Wilbeck and Rand [6] demonstrated that this type of material provides a good substitute bird material. The gelatine was located in a sabot which was stripped just before the impact so that only the gelatine hit the specimen. The velocity of the sabot was measured with two photodiodes and the event was filmed with a high speed camera.

In each test, the specimen was rigidly clamped on three sides and impacted at an angle on the leading edge. Each type of profile was subjected to impacts of increasing velocity until ductile tearing of the leading edge was obtained. This appeared to be caused by tensile strain on the reverse of the plate. Confirmation of this was obtained by inspection of the plates after the impact where leading edges showed an increasing deformation with increasing impact velocity until failure occurred on planes inclined at 45° to the surface.

By increasing the impact velocity in steps a critical velocity range was obtained below which the profile failed in Mode A and above in Mode B. This critical velocity range differed quite considerably for each profile type. Table 1 shows the critical velocity range normalised to the lowest impact velocity.

From a post-impact analysis of the profiles it was found that the maximum deformation increased with increasing impact velocity for Mode A failure. As failure type changed to Mode B (tearing) the maximum deformation was reduced and localised at the point of impact, indicating that failure occurs early in the impact. Also, the maximum longitudinal strain along the leading edge of the plate was an order of magnitude greater than the transverse strain perpendicular to the leading edge.

3.3. Mathematical modelling

From the experimental test programme it was established that the leading edge profile governed impact resistance. The DYNA3D code was used to determine whether it was possible to use a simplified methodology to calculate the critical failure velocity based on the experimental test results. The soft body impact was approximated by a stepped input pressure together with a strain-rate sensitive constitutive relation model the response of the plate during the early stages of the impact. Comparisons could then be made between the behaviour of the different profile types so as to determine a critical impact velocity. From the tests on cylindrical specimens it was seen that the material response at strains up to 6 %, could be described, as elastic / perfectly-plastic but with a rate dependent yield stress. Therefore, a strain rate dependent isotropic elastic perfectly plastic constitutive relation was used.

Great care was taken to model the geometry of each type of profile. Due to symmetry only half models were used, an "encastre" condition was applied to the supported sides with the leading edge remaining free.

Simple momentum considerations were needed to relate the pressure on the leading edge to the impact velocity, density and angle of impact of the gelatine projectile. A stepped input pressure was used, with the step length determined by the time taken for the maximum velocity of the model to reach the required impact velocity. The oblique impact was approximated to an area loading equivalent to a quarter ellipse

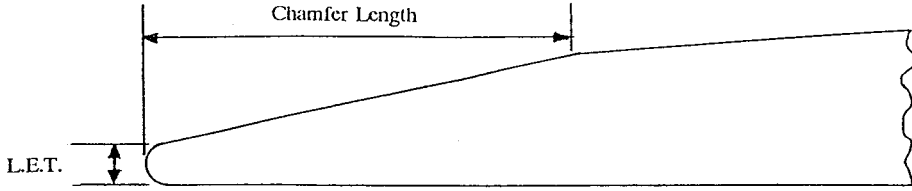


Figure 4. Geometrical Parameters of Leading Edge Profile

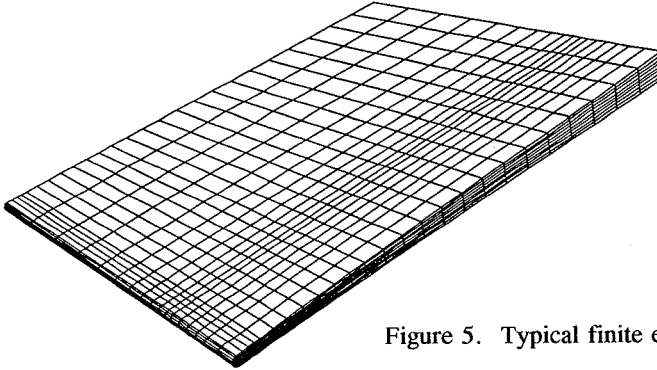


Figure 5. Typical finite element mesh

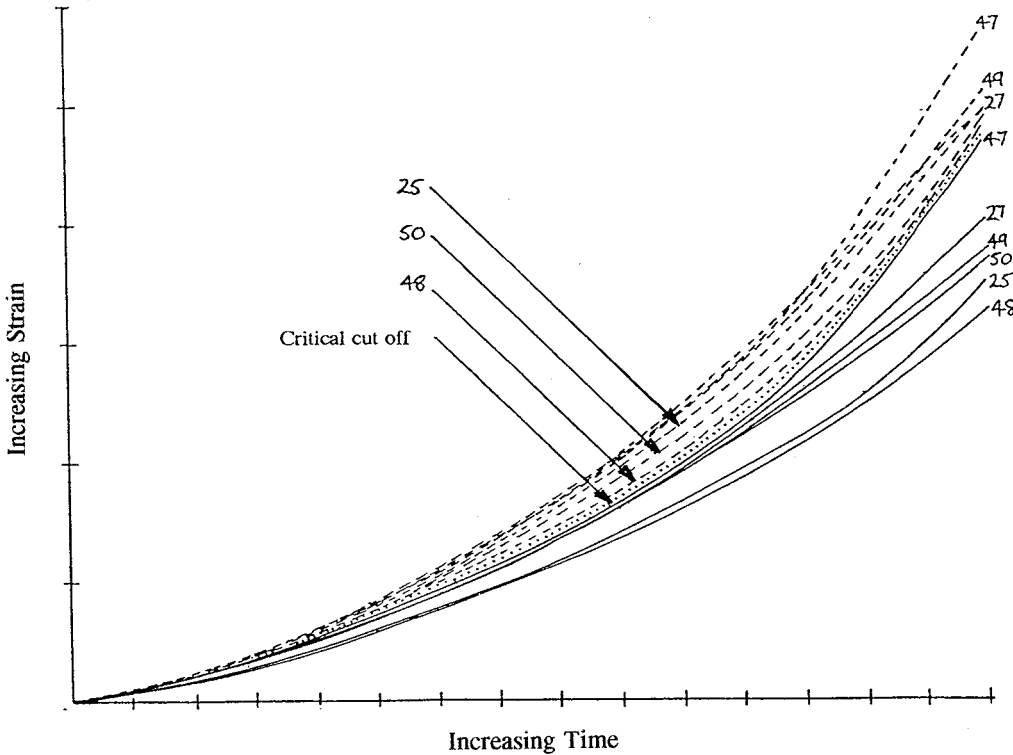


Figure 6. Graphical representation of profile responses

as shown in figure 5. The input velocities for each profile type were related to the upper and lower values of the range of critical velocities obtained from the experimental programme. Mode B or tearing failure was found to be of a ductile type originating on the reverse of the specimen and caused by elongation of the leading edge. Therefore, the most critical component in the finite element analysis was the tensile strain on the reverse of the leading edge. Figure 6 graphically represents for each profile the variation of this tensile strain with time. In figure 6 the dotted lines represent the strain-time curves at the upper critical velocity for each profile, corresponding to Mode B and the solid lines relate to the lower critical velocity, Mode A failure. Clearly, it can be seen that there is a "cut off" line between failure and survival. This line represents the critical response of each profile to cause failure. In order to calculate the critical impact velocity the impact pressure / velocity of each profile type was adjusted until the resultant response equalled the critical response. Table 1 indicates the critical velocities for each type of profile. The calculation of the critical velocity of failure by this method gives good agreement with the experimental test results.

4.0. CONCLUSION

It has been shown that even when a very simple constitutive relation is used to define the material behaviour a combined programme of experimental tests and mathematical modelling allows a good estimate to be made of the critical impact velocity to cause failure. The modelling was limited to plastic strains up to about 6 %. A more accurate constitutive relation is needed if a more detailed modelling of the deformation process is required.

Profile Number	Leading Edge Thickness	Chamfer		Lower Velocity	Upper Velocity	Critical Velocity
		Type	Length			
47	100 %	Single	0	113	145	123
48	29 %	Single	1.2 %	2	74	48
49	29 %	Single	3.3 %	0	39	23
50	50 %	Single	2.5 %	68	87	78
25	72 %	Double	3.3 %	41	93	88
27	50 %	Double	3.3 %	46	77	63

Table 1. Experimental details of leading edge specimens.

5.0. REFERENCES

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