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Large Scale Impact Tests on 50 mm Diameter Tensile Samples - Correlation of Experimental Results with Finite Element Models

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Abstract. Experimental work is being undertaken on the 1 megajoule railway impact track at the UK Health & Safety Laboratory to assist in the validation of explicit-dynamics finite element codes. Large diameter tensile samples are being fractured at strain rates of 20 s^{-1} to provide data which is compared with the output of a finite element program. This should verify the modelling accuracy of observed failure modes and elasto-plastic behaviour. Dynamic material properties are usually derived from tests on small samples, and should this work reveal a 'size effect' then current finite element codes and dynamic material properties may need to be re-assessed.

Résumé : Des travaux expérimentaux sont effectués sur un rail d'impact ferroviaire d'1 mégajoule au Laboratoire d'Hygiène et de Sécurité afin de faciliter la validation de codes d'éléments finis de dynamique explicite. Des échantillons de traction de large diamètre sont fracturés à des cadences d'effort de 20 s^{-1} pour fournir des données qui sont comparées aux résultats d'un calcul aux éléments finis. Ceci devrait vérifier la précision de la modélisation des modes de défaillance observée et du comportement élastoplastique. Les propriétés dynamiques du matériau sont en général dérivées d'essais sur de petits échantillons et si ces travaux révèlent un effet d'échelle, les codes d'éléments finis actuels et les propriétés dynamiques du matériau pourraient alors devoir être revus.

1. INTRODUCTION

Safety assessments for many large structures in critical applications such as offshore production platforms and nuclear power generation plants are usually performed using the information provided by finite element analysis. Determining the response of these structures to static and particularly dynamic loading has to be done using computer modelling since testing full-size or scale models is often impractical or extremely expensive. When dynamic analyses are conducted *e.g.* to model the effect of seismic forces on reactor supports, they utilise dynamic material properties usually gained from basic laboratory tests performed on small samples - *e.g.* the Split Hopkinson Pressure Bar test. The results from small scale tests may not be applicable to larger structures or components due to the potential for size effects - particularly in post-yield behaviour.

The aim of the work being conducted by the Health & Safety Laboratory in Buxton, England, is to determine whether there are significant differences in the material behaviour when a 50 mm diameter structural steel sample is loaded in tensile impact compared with that predicted by dynamic finite element techniques. Implications of this work may be considerable - the test results may verify that dynamic material properties determined from small samples are accurate and hence valid for use in finite element codes (they may even be too conservative) or they may highlight that a size effect is present and that material properties ought to be re-assessed to determine more accurate dynamic stress-strain relationships, particularly when applied to 'real-world' engineering components [1].

To date, a testing programme on a limited number of structural steel samples has been completed, and the results are being processed to determine the actual stress-strain behaviour. Finite element modelling is currently being undertaken to determine whether it is able to accurately predict the results that were obtained experimentally. Future work currently being planned with the UK Health & Safety Executive's Nuclear Safety Division will investigate the observed behaviour of other types of steel with that predicted by finite element codes currently used by the nuclear industry.

2. TENSILE IMPACT TESTING

2.1 Experimental configuration

The Health & Safety Laboratory's railway impact track (Figure 1) has been used to test 50 mm diameter tensile samples of BS4360 grade 50D weldable structural steel (Figure 2) which is widely used in the offshore industry. The track, consisting of opposing 90 metre 1:7 slopes and capable of inputting up to 1 megajoule of impact energy, uses a 3500 kg 'hammer truck' moving at approximately 13 ms^{-1} as the impactor to produce the 70 kJ required to break the sample. The tensile specimen - with a sectional area of 1964 mm^2 , a gauge length of 250 mm and weighing approximately 35 kg - was mounted in a 9000 kg loading truck held stationary on the track and impacted by the hammer truck and loading the specimen in tension (Figure 3). The applied strain rate was not known exactly before testing since the characteristics of the rig and sample were not known; it was however estimated to be approximately 25 s^{-1} .

Figure 1: HSL railway impact track

Figure 2: 50mm diameter tensile sample

2.2 Instrumentation & data analysis

To record the forces on the sample that occurred during the impact event each sample had eight strain gauges bonded to it (Figure 4). Three high elongation (+20%) gauges were fixed at the quarter-, mid- and three-quarter points on the 250 mm gauge length to record strain up to and beyond the elastic limit. Four standard elongation gauges (+3%) at 90° intervals were bonded on the 100 mm diameter portion to record the gross force on the sample (since the material in this part of the sample should remain elastic), and any bending effects since perfectly linear impact loading could not be guaranteed. One short gauge length

device was bonded on the 'struck' end of the sample to provide an additional force measurement point and also permit measurement of the stress wave in the material since it would record strain several microseconds before the gauges at the opposite end of the sample.

Figure 3: Impact trucks

Figure 4: Tensile impact sample

Measurement of the strain on the sample during the impact event was done using a 12-bit digital logger recording at 250,000 samples per second. Pre-calibration was conducted using precision resistors shunted over the dummy gauges in the Wheatstone Bridge to simulate tensile strain, and the results were used to calculate the actual strain during the impact event. Gross specimen gauge length strain was derived from images recorded by a LineScan camera system - a specially-developed non-contact optical technique recording at 6500 samples per second and outputting a grey scale image which when analysed by computer produced the gross strain on the gauge length. A high-speed digital video and motion analysis system has also been used to augment the force and displacement data and provide visual correlation of the fracture behaviour, particularly in the region where 'necking' of the sample occurs.

3. FINITE ELEMENT MODELS

Results from the experiments are to be compared with those predicted by the use of explicit transient dynamic finite element analysis using the LUSAS system. The aims of the comparison are to indicate whether dynamic performance of a well-pedigreed material can be accurately modelled and to determine if refinement of the dynamic tensile stress-strain relationship for the material is needed.

The models used for results correlation will be initially two-dimensional, axisymmetric models using explicit-dynamics quadrilateral elements. Subsequent refinements of the model will proceed to include a full three-dimensional analysis with solid continuum hexahedral elements. Analysis is to be conducted in 'prescribed displacement' mode where the sample in the model is subjected to the same displacement-time history as was observed on samples tested in the experimental programme. The outputs will serve to show whether the strain-time history as recorded during the tests was the same as that predicted by the analytical models. The initial material models used assume isotropic behaviour with linear plasticity, although analysis with non-linear plasticity will also be conducted to try to improve accuracy if sufficiently detailed and complete materials data is available. Should discrepancies arise between the predicted and the observed behaviour, it is initially intended to use data from the experiments to produce a revised hardening curve for the post-yield conditions of the material. Other approaches, as yet undefined, may also be employed.

4. EXPERIMENTAL RESULTS

Results on the tests conducted to date (Table 1) indicate that there appears to be a marked difference between pseudo-static and impact tests. The material tested was stated on its mill certificate as having 27% ultimate elongation, a figure confirmed by the pseudo-static test (0.0005 s^{-1}) which showed 26.4% elongation and an energy to failure of 69 kJ. Subsequent impact tests have shown consistently higher energies and greater elongations to failure. Initial strain rates shown by the gauges on the 250 mm gauge length indicate instantaneous input strain rates of approximately 30 to 50 s^{-1} , although the gross strain rates (total strain on gauge length divided by impact event duration) have averaged approximately 20 s^{-1} .

Table 1: Results Summary					
Test	Input energy	Gross strain rate	Peak force	Elongation (250 mm GL)	Strain energy
	kJ	s^{-1}	kN	mm (%)	kJ
Static A	-	0.0005	1,215	66 (26.4)	69
Impact B	276	17.3	1,700	80 (32.3)	115
Impact C	300	26.5	1,356	78 (31.2)	91
Impact D	294	22.9	1,387	78 (31.2)	81
Impact Z †	192	9.1	1,864	50 (20)	56
Impact Y §	221	12.2	1,218	35.4 (11.8) §	35
† - sample did not break, second impact (§) conducted. § - data based on 300 mm gauge length (250 mm original + 50 mm plastic strain from Impact Z)					
Impacts Z & Y combined (on 250 mm gauge length)				85.4 (34.2)	90

A comparison between the static and impact tests may be seen in Figure 5. It is evident from this graph that in addition to the apparently higher yield stress observed in the dynamic test, the elongation of the sample tested dynamically up to the point of fracture (*i.e.* before any elastic recovery occurring *after* fracture) is almost 5% (or 12 mm on 250 mm gauge length) greater than the static test. The nominal force levels are also greater - the dynamic test absorbs 77.1 kJ of strain energy to reach the same elongation as the static test. It is clear, though, that the main source of apparent additional energy absorption capability is due to the increase in ultimate elongation. In order to provide extra verification of this, it may be necessary to conduct tests on additional smaller samples and also on non-standard samples geometries *e.g.* shorter gauge lengths at 50 mm diameter, or reduced diameter at 250 mm gauge length.

Figure 5: Comparison of static & impact tests on large diameter samples

Tests have also revealed the occurrence of 'double necking'. In three of the four samples tested dynamically fracture did not occur at the middle of the gauge length, and it was noticed that as well as the necking down at the fracture surface, there was also a slightly necked portion further along the gauge length. Initial measurements indicate that the two regions where necking is seen are symmetric about the middle of the gauge length. This may be due to one of several factors; stress waves propagating (and reflecting) along the sample length or perhaps that the sample is assuming a mode shape due to the impact event and that necking possibly occurs at the node points. It is intended, if time permits, to conduct modal analyses on the test sample and associated hardware to determine if the natural frequency of the system has any influence on 'double necking'. Temperature measurements on the samples taken immediately after the impact tests have shown surface temperatures in excess of 70°C. It is possible that thermal imaging may be used on subsequent tests to show the thermal effects during an impact event, and then to determine if this has any bearing on the energy absorption performance of the material.

Figure 6: Sample after (static) test

5. CONCLUSION

Experimental data collected to date reveals that there is greater ability for large diameter samples tested dynamically at strain rates of approximately 20 s^{-1} to absorb more energy than when tested statically. Currently ongoing finite element analysis is being conducted to endeavour to reveal if this phenomenon is predictable, or indeed if it is a 'size effect' not observed in smaller samples of the same material, and hence not forming part of the data set defining the material behaviour.

Further more detailed finite element model validation and refinement is intended, and future experimental work to be conducted by the Health & Safety Laboratory in this field may include widening the range of materials and sample geometries tested to those used in other sectors of industry, with the overall aim of ensuring that design codes and computer models used to specify the dynamic performance of structures and components truly reflect the dynamic properties of the materials used.

Acknowledgements

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Reference

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