L.D.T.F.: A Large Test Facility for the Investigation of the Dynamic Behaviour of Structures

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Abstract

The construction of a large dynamic test facility has been completed at JRC Ispra. The machine is designed for a maximum load of 5 MN and can test to rupture steel specimens of up to 5000 mm^2 cross-section and 1 m length at strain rates of 5 - 100 s^{-1}. Preliminary tests have demonstrated the operability of the device and have also been used to calibrate a 1-D numerical model of the machine. A series of systematic tests on austenitic steel specimens, either virgin or containing defects, such as welds or notches, has been started.

1. Introduction

A reliable analysis of the behaviour of structures under accident conditions, such as those occurring in hypothetical transients in nuclear reactors (aircraft impacts, power excursions, earthquakes, etc.) as well as in conventional plants, requires an appropriate knowledge of the dynamic properties of structural materials over a wide range of strain rates. Over the years, many dynamic experiments [1,2,3] have been performed at JRC using various test facilities on relatively small specimens. However, it is not always easy or even possible to extrapolate results obtained on such small specimens to large real structures, e.g. in case of welded joints, local defects, etc. Also, tests on particular non-homogeneous structural materials such as concrete necessarily require the use of large specimens. Therefore, a new Large Dynamic Test Facility (LDTF) has been set up at JRC Ispra, which allows dynamic testing of large specimens, up to typically 5000 mm^2 cross-section and 1 m length (for stainless steels).

2. Test Facility

The LDTF layout is presented in Fig. 1. In the present configuration, the machine consists of two 100 m long cables (1), aligned along the same axis, which can be prestressed by means of hydraulic pistons (2) up to a load of 5 MN. In Fig. 1 only one half of the machine is represented, since it is symmetric. Each cable consists of 34 parallel steel strands connected to the heads (3) and (4). Head (4) transmits the load to rod (5) and to the crossbar (6), which is connected to the supporting structures by means of two explosive bolts (7). Rod (5) transmits the load to the specimen (8) through a cleave (9).

The initial cable load is normally shared between the explosive bolts and the specimen, the latter taking a small fraction (which can be prescribed) of the total load, so as to have a known prestress on the specimen which eliminates any initial gaps in the transmission and yields cleaner experimental results. The experiment is initiated by firing the bolts. The initial cable load is released and stress waves propagate along the structure and reach the specimen which is deformed. At the same time, stress waves are propagated also along the cables, reach the hydraulic piston, are reflected and return to the specimen. The 100 m cable length has been chosen in order to obtain a time interval of about 40 ms of relatively undisturbed loading conditions on the specimen, before arrival of the reflected wave. Depending on cable preload, and specimen size and material, the specimen deformation can reach very high values, up to rupture. In case of specimen rupture, the remaining energy is absorbed by hydraulic dampers (10).

The nominal value of the specimen strain rate $\dot{\varepsilon}$ can be varied from test to test by changing the cable preload F_o, the specimen length L and the specimen "strength" F (product of cross-section and flow stress) according to the relationship:

$$\dot{\varepsilon} = K \frac{(F_o - F)}{L}$$

The actual mean specimen strain rate obtained in a test oscillates around this value, due to the presence of concentrated masses and geometrical discontinuities in the machine. For stainless steels, typical mean strain rates in the range 5 - 100 s^{-1} can be obtained on specimens of up to 5000 mm^2 cross-section.

For the moment, the device is one-dimensional (two aligned cables), however, the construction of a second pair of "arms" perpendicular to the first one has been foreseen in the design, to permit biaxial testing.

During an experiment, the strain is measured at various positions on the LDTF. Typically, three strain gauges are placed at intervals of about 110 mm on the transmission rods, which always remain elastic. These signals should permit the estimation of the force acting on the specimen. Strain measurements are also taken directly on the specimen, both on the plastic part (near the center) and on those parts, near the cleaves, which always remain elastic. Plastic strains of up to about 20% can be directly measured by strain gauges, while for higher values, up to rupture, optical methods (high-speed films, non-contacting displacement transducers, Moiré interferometry) are used.

3. Calibration Experiments

After construction of the LDTF, a series of tests has been performed in order to check the machine operability. First of all, the machine has been statically loaded in order to measure the deformation of the various components under nominal load conditions. As can be seen in Fig. 1, the synchronism of the explosive bolt ruptures is a crucial point in order to avoid asymmetric loading during the experiment and possible damage to the machine; therefore, an investigation has been performed on the geometry, material and thermal treatment of the bolts as well as on the synchronism of the firing system. The best results have been obtained with the geometry shown in Fig. 2 (for a machine operational load of 2.5 MN). The explosive charge is placed in a transversel bore in the cylindrical part of the bolt and a circumferential V-notch is machined all around it in order to initiate rupture. The explosive is fired by means of a high-voltage detonator. The synchronism of the detonations, which is essential in order to obtain synchronism in rupture, has been checked by placing 4 detonators on the corners of a square steel plate and by connecting them along the plate sides with 4 thin strips of explosive material. When the 4 detonators are fired with a single pulse, detonation waves start from the corners and proceed towards the adjacent detonators until they meet. The meeting points are clearly impressed on the plate, and this allows the measurement of the time delay between the various detonations, with a precision of 0.3 μs (taking into account that the velocity of a detonation wave is about 7.5 mm/μs for our explosive). The resulting maximum measured delay was smaller than .3 μs.

The rupture timing check during a real experiment has been obtained by measuring the load acting on the bolts. Fig. 3 shows the unloading of the 4 bolts due to rupture. The maximum scatter of the rupture times which has been measured is of the order of a few milliseconds. Up to now, about 15 tests have been performed without any synchronism problems.

The hydraulic dampers have also been tested, by operating the machine without a specimen. When the bolts are fired, the dampers absorb the energy stored in the machine; the dynamic response of the dampers (velocity as a function of load) has also been measured and will be used in the pre-calculations of future experiments.

The machine behaviour during a real experiment has been tested in about 5 shots with low carbon steel specimens having a cross-section of 2000 mm^2 over a length of 400 mm, at different preloads (1.5 - 2.0 MN). The samples were instrumented with strain gauges and the overall motion was filmed at 5000 frames per second. No substantial movement of the specimen centerline has been observed from the films up to rupture, thus demonstrating the symmetry of the loading. Also after rupture, the movement of the specimen heads continues regularly up to the final arrest by means of the dampers.

4. Numerical Modelling

The main purpose of the experiments is to investigate the behaviour of the specimen, i.e. to characterize the dynamic material properties, e.g. as a function of strain rate, or the structural behaviour, in case of large specimens containing real "defects" such as weldings. The starting point of such an investigation is the measurement of signals, normally strains, taken at various locations on the machine itself (transmission rods) and on the specimen. In analysing the experimental data, it is essential to discriminate between specimen response and effects of the machine geometry. For this reason, it is necessary to have a very good knowledge of the behaviour of the machine itself, e.g. by a numerical model able to reproduce it. Since the machine geometry, apart from a few local complicated parts (the cross-bar and the cleave, see Fig. 1), is essentially one-dimensional, it has been attempted to represent it by a simple 1-D model, which is very convenient from a computational point of view.

In the past, the computer code EURDYN-1D [4] had been used to predict some of the machine capabilities in the design phase. More recently, after construction of the LDTF, the code has been used to obtain a one-dimensional model of the machine, which has been validated by comparison with ad-hoc experiments. EURDYN-1D is a finite-element computer code for the non-linear dynamic analysis of one-dimensional structural systems. It uses linear lumped-mass 1-D elements with explicit central-difference time integration and is particularly suited for wave propagation problems in solids. Special elements such as "gaps" and semi-infinite boundary elements allow the treatment of particular problems like impacts and very long structures (like the LDTF cables), respectively. Very general structural systems composed of various 1-D parts in parallel, connected by junctions (e.g. the main LDTF body and the hydraulic dampers, see Fig. 1) can be treated as well. The code also offers the possibility of including numerical damping and friction effects. The code is coupled to the TPLOT [5] system, for data management and production of time histories.

To characterize the machine behaviour, special-purpose experiments have been performed, using a "specimen" with known properties. This was simply a bar with a relatively large cross-section so that it always remained elastic during an experiment. The measured signals thus outlined the effects of the machine behaviour. These results have been used to calibrate the numerical model.

One half of the LDTF (by symmetry) has been modelled by 380 1-D elements. The discretization includes only a short part of the cables (250 mm) and a semi-infinite boundary element is used to simulate the rest of the cable. The actual distribution and actual (linear elastic) properties of the material have been represented in the model. The only parameter assumed for calibration is the Young's modulus (or the elastic deformability) of the part representing the cleave. The reason of this choice is that the present cleave (specimen attachment) is the most complicated part, including two concentric threads and a transverse pin subject to bending.

By varying the cleave's Young's modulus in the model, it has been possible to reproduce the experimental results to a satisfactory degree of accuracy. In particular, the first peak and the steady-state long-term strain values are correctly reproduced by the model. However, the oscillations following the first peak have a smaller amplitude in the experiment than in the model. This is thought to be due to the presence of dissipative phenomena (friction) in the real experiment. As a matter of fact, by introducing in the model a friction term in the cross-bar region (where the moving parts of the machine are in contact with the frame), the agreement becomes even better. Fig. 4 compares the experimental scatter of two ad-hoc tests, using an elastic specimen as explained above, with the model calculated response (including friction) in the transmission rods (a) and in the central region of the specimen (b). This has been obtained by assuming a "fictitious" Young's modulus of the cleave model about 12.5 times smaller than the actual cleave material modulus. A static measurement of the cleave deformability is in very good agreement with the value that has to be assumed in the model in order to fit the dynamic experimental data.

This numerical model is also particularly useful in the testing phase of the machine and helps in defining suitable geometrical changes in the experimental set-up after the first preliminary tests. It is also to be used for pre-calculations of real experiments and as a continuous numerical support tool for the experimental activities.

5. Conclusions

The preliminary phase of the LDTF experimental programme has been completed, demonstrating that the facility can be safely operated up to a load of 2.5 MN. The extension to the design load (5 MN) is foreseen in the near future.

A 1-D numerical model of the machine has been obtained and validated with ad-hoc elastic experiments, thus demonstrating that the overall behaviour of the machine is essentially one-dimensional.

A first test with a real specimen of AISI 316L stainless steel having a cross-section of 2000 mm^2 over a length of 350 mm has been performed. Fig. 5 shows the time history of the mean strain measured from the high-speed film over different gauge lengths of 75 - 250 mm on the central part of the specimen. It can be seen that: a) the mean strains (taken over different lengths) are uniformly distributed over the entire constant cross-section part of the specimen; and b) the strain rate is fairly constant up to about 16 ms when the specimen necking begins, except for the very beginning of the deformation (first 2 ms). Preliminary calculations indicate that this transient could be substantially reduced by some minor modifications in the machine geometry.

A series of systematic tests on austenitic steel specimens, both virgin and with defects (weldings, notches, etc.) is underway.

References

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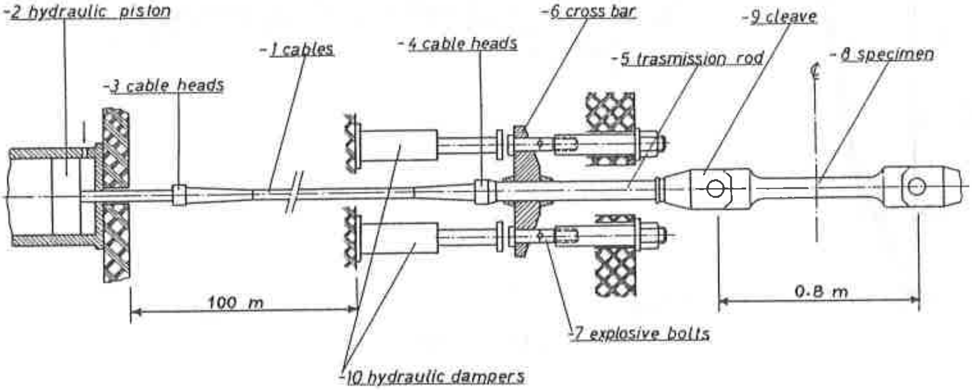

FIG. 1 -GENERAL LAYOUT OF L.D.T.F.

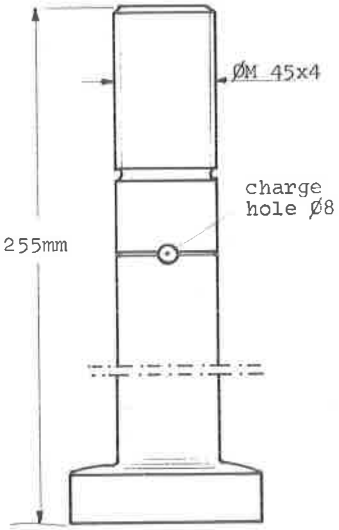

Fig.2:Explosive bolt

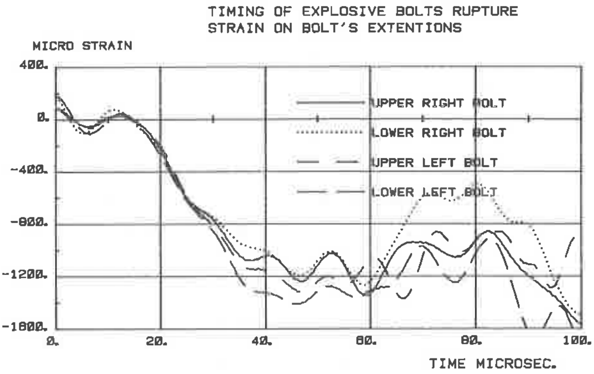

FIG. 3 - CHECK OF DETONATION SIMULTANEITY

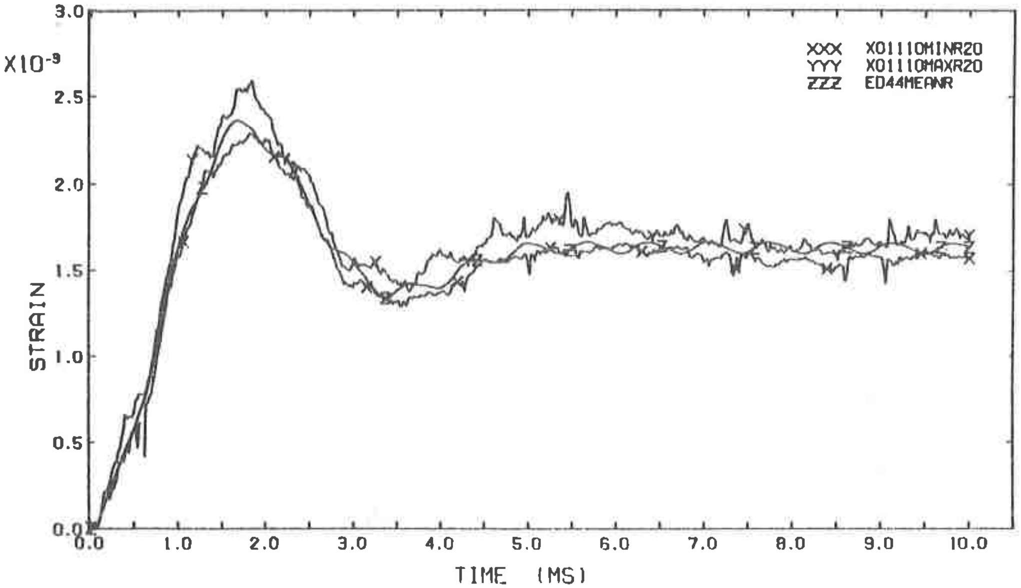

FIGURE 4 A) X.Y : EXPERIMENTAL SCATTER FOR ELASTIC TESTS
(SIGNALS ON THE TRANSMISSION RODS)
Z : EURDYN-1D CALCULATION

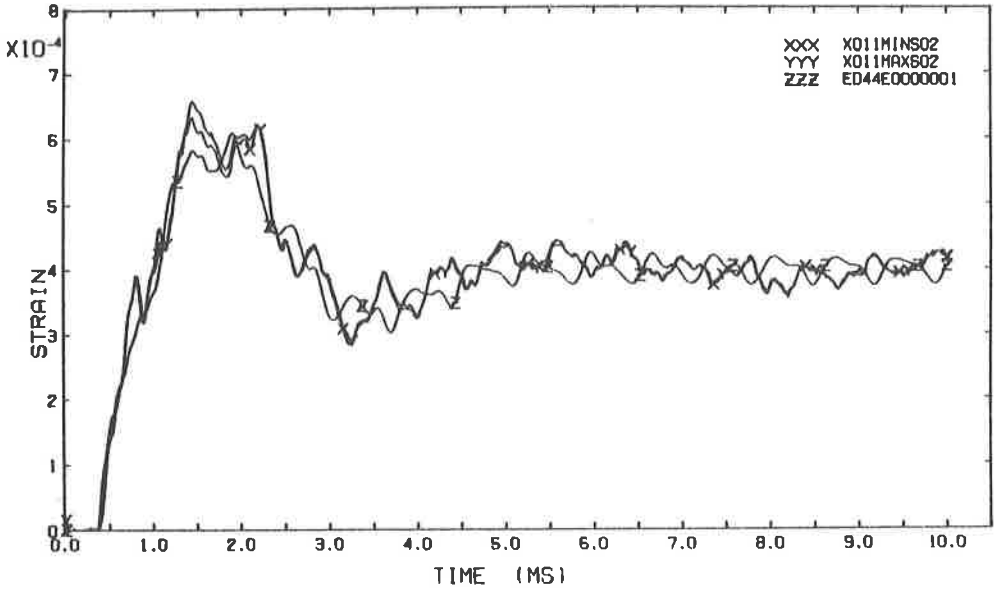

FIGURE 4 B) X,Y : EXPERIMENTAL SCATTER FOR ELASTIC TESTS
(SIGNALS AT THE SPECIMEN CENTER)
Z : EURDYN-1D CALCULATION

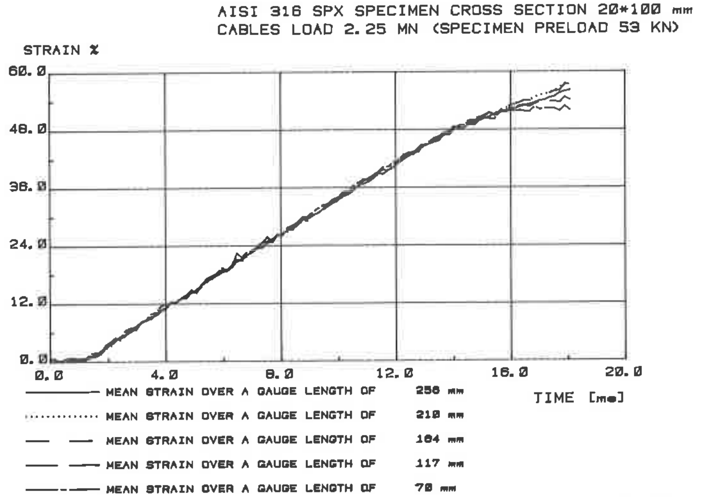

Fig.5: Specimen deformation history from high-speed film.