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Cong Tu Nguyen, H. Schindler. On Spurious Reflection Waves in Hopkinson Bar Tensile Tests Using a Collar. *Journal de Physique IV Proceedings*, 1997, 07 (C3), pp.C3-85-C3-90. 10.1051/jp4:1997317 . jpa-00255461

HAL Id: jpa-00255461

<https://hal.science/jpa-00255461>

Submitted on 4 Feb 2008

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On Spurious Reflection Waves in Hopkinson Bar Tensile Tests Using a Collar

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Abstract. In order to investigate the effect of the spurious waves present in the Hopkinson bar tensile testing technique using a collar, tests are performed with different set-ups (simple and net-shaped collars, normal and cut specimens) and different specimen materials (steel, aluminum and polyethylen). Numerical simulation (using the FD dynamic code AUTODYN-2D) is also done to support the experimental results. The transfer of the incident compressive pulse through the collar can not be perfect, because of spurious waves which reflect at the end surface between threaded specimen and input bar. They interfere with the measurement signals from the tensile specimen and lead to a (fictitious) tensile pre-stress. The cause for this effect is the actual set-up used for the tests having a same length for the input and output bars.

Résumé. Pour étudier les réflexions perturbatrices présentes dans la méthode avec collier de l'essai de traction avec barres d'Hopkinson, des essais sont conduits avec différents dispositifs (colliers simple et épousant la forme, éprouvettes normale et coupée) et différents matériaux d'éprouvette (acier, aluminium et polyéthylène). Une simulation numérique (au moyen du code FD dynamique AUTODYN-2D) est aussi faite en support à ces essais. Le transfert de l'onde de compression incidente au travers du collier ne peut être parfait, en raison d'ondes perturbatrices qui réfléchissent à la surface en bout entre éprouvette vissée et barre d'entrée. Elles interfèrent avec les signaux de mesure provenant de l'éprouvette de traction et aboutissent à une précontrainte de traction (factice). La cause en est l'actuel dispositif d'essai ayant une même longueur pour les barres d'entrée et de sortie.

1. INTRODUCTION

The split Hopkinson pressure bar apparatus at EMPA, which was designed for compressive tests at high rates of strain up to 10^4 s^{-1} , was modified such that it also allows tensile tests to be performed. This was achieved by using threaded tensile specimens between the two bars and a collar that shields the specimen from the initial compressive pulse, as introduced by Nicholas [1]. Compared with the compressive tests, there are some additional experimental difficulties to be dealt with. Firstly, because of mismatches concerning the elastic impedance that are inevitable in the case of tensile specimens, disturbing wave reflections occur. Secondly, the stress pulse has to travel twice across the composite connection area of bars/specimen/collar (from the input to the output bar and then backwards) before the actual signals can be measured, which increases the problems with dispersed waves due to air gaps and threading. Thirdly, because the tensile specimens that are threaded to the bars have a relatively small cross-section compared to the one of the compressive specimens, the strain-gage signals that serve as the basis for the evaluation of the stress-strain curve are generally of a smaller magnitude, thus more difficult to be evaluated in presence of spurious waves. As some preliminary experiments have revealed, these spurious waves interfere with the stress signal of the specimen. Depending on the tested materials, they can be of a higher magnitude than the signals that contain the stress-strain information, leading to a stress-vs.-strain curve that is unrealistically high. This is the case especially when testing materials of low elastic modulus, density and strength, such as plastics. In order to clarify these effects and to explore ways to improve the measured signals correspondingly, several tests using different specimens and set-ups were performed. In addition, the tensile process was simulated numerically.

2. EXPERIMENTAL SET-UP

Figure 1 shows the set-up used for these dynamic tensile tests by means of the split Hopkinson pressure bar apparatus. The bars (diameter 10 mm) and the collar were made of maraging steel. Both the input and output bars were 1 m long. The stress pulses were monitored by two pairs of strain gages (#1 and #2) that were mounted on each bar, at equal distance of 400 mm from the faces of the specimen. The striker bar was also 400 mm long. To allow the initial compressive pulse to be transferred to the output bar without doing any harm to the specimen, a hollow cylinder with an inner diameter of 5 mm and made of maraging steel was used as a collar. Being one of the key elements of this testing technique, other collar designs have also been considered, as discussed in section 6.

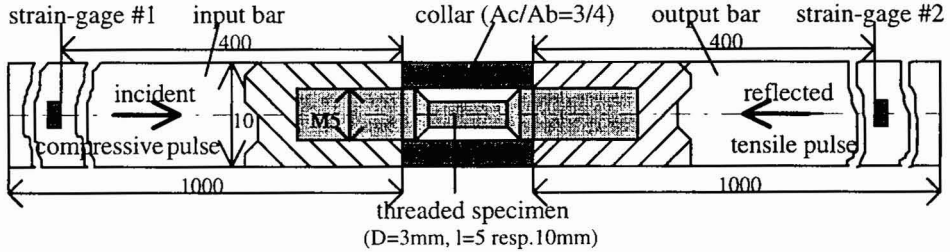


Figure 1: Set-up for Hopkinson bar tensile tests using a collar.

The tensile specimens used in this investigation (diameter 3 mm, thread 5 mm) were made of three different materials concerning density, strength and E-modulus: medium-strength steel (DIN 100MnCrW4), pure aluminum (99.7%) and polyethylen (HD-80), and two different gage lengths (5 mm for upper and 10 mm for lower strain-rates, respectively).

3. EFFECTS OF SPURIOUS REFLECTION WAVES

Even if care is taken to form the connection between input and output bars (by the tensile specimen and the collar) as smooth as possible, there are some inevitable gaps in the thread and between the specimen and the collar and - in case of different materials - mismatches of the elastic properties, which give rise to wave reflections when the incident compressive pulse passes this connection. In a simplified theoretical view one can interpret the collar and the specimen as a massless elastic element of a stiffness k that connects the input and output bars. The stiffness k can be estimated by

$$k = \left(\frac{\ell}{E_{coll} \cdot A_{coll} + E_{spec} \cdot A_{spec}} - \frac{\ell}{E_0 \cdot A_0} \right)^{-1} \quad (1)$$

where ℓ denotes the length of the collar, E_0 , E_{coll} and E_{spec} Young's modulus of the bars, the collar and the specimen, respectively, and A_0 , A_{coll} and A_{spec} the corresponding cross section areas. According to basic elastic wave theory [2, 3], a rectangular pulse of a magnitude σ_0 is reflected by this elastic connection back to the input bar as a wave of the shape

$$\sigma_r(t) = -\sigma_0 \cdot e^{-\frac{k \cdot t}{A_0 \cdot Z}} \quad (2)$$

where $Z = \sqrt{E_0 \cdot \rho}$, with ρ denoting the density of the bars.

Obviously, in reality the reflected peak is less sharp and of smaller magnitude than described by (2), due to damping, dispersion and - first of all - the finite length of the collar and specimen, which gives rise to higher frequency waves that disperse the theoretical peak. Since the cross-section of the collar and the

one of the input and output bars are partly in direct contact, the magnitude of the reflected main peak will not exceed the corresponding part of the initial pulse magnitude σ_0 , thus the magnitude of the peak given by (2) is reduced to about

$$\sigma_r = \frac{A_0 - (A_{coll} + A_{spec})}{A_0} \cdot \sigma_0 \quad (3)$$

The purpose of the above rather crude theoretical considerations is not to predict quantitatively the reflected waves, but only to give some rough, qualitative relations that are useful for the interpretation of the strain gage signals, which are shown and discussed in the following by examples. To obtain the spurious reflected waves as pure and intense as possible (see Eqs. (2) and (3)) and to isolate them from the actual signal that is produced by the tensile fracture process of the specimen, some of the tests were performed using specimens that were split in two parts by a cut along its central cross-section. In these cases, the tensile stresses in the input bar, that serve as the basis for the stress-vs.-strain curve to be evaluated, are due to the spurious waves only, since the specimen is unable to introduce tensile stresses into the input bar.

An example of the resulting strain signals, obtained from the strain-gages #1 and #2 (Fig. 1) for a test with a cut steel specimen at an impact speed of 20.5 m/s, is shown in Figure 2. Therefrom one can see that a sharp tensile wave (peak A) is reflected from the connection between the input and output bar back to the input bar, whereas the main compressive pulse - as the signal of strain gage #2 reveals - is transmitted to the output bar essentially unchanged. (In the present set-up it takes about 210 μ s for a stress pulse to travel across the 1 m long input and output bars, and the time delay due to the 400 mm distance of the strain gages from the specimen is about 85 μ s.) Peak A is followed by a compressive peak B, which represents the reflection emitted at the specimen/collar location when it is passed by the end of the initial compressive pulse. At about $t = 430 \mu$ s, peak A' arrives, which represents the reflection of A at the front end of the input bar, heading towards the specimen. It arrives at the specimen just at the same time as the main tensile pulse that comes from the rear end of the output bar. The latter imposes a tensile force on the specimen, thereby loosening the contact between the collar and the bars and forming - in the present case of a cut specimen - essentially free ends of both the input and the output bar. Thus, peak A' is fully reflected as a tensile wave A'' back into the input bar, whereas the tensile pulse in the output bar, which would cause the tensile loading in the normal case of a tensile specimen, is fully reflected as a compressive pulse back into the output bar. The twice reflected peak A'' arrives at strain gage #1 at about $t = 600 \mu$ s, i.e. just when the stress signal C from the tensile test is expected to arrive. At the same time, peak B', which is a reflection of B at the front end of the input bar, passes this location. Thus, the measured signal C represents a superposition of the reflected peaks A'' and B'. If this signal is evaluated by the usual procedure of split Hopkinson bar testing technique [4], one obtains a stress-vs.-strain curve, as shown by the dotted line in Figure 3. Obviously, since a split specimen is used, this curve is in no way related to the actual strength of the material. These experiments clearly show that the spurious waves have to be accounted for when performing tensile tests using a collar.

As can be seen from the two strain gage signals shown in Fig. 2 there is a shift in the zero-strain-level after the first reflection of the main pulse. The reason for this shift is not clear at present time. It has been disregarded in the present discussion and evaluation.

4. EVALUATION OF TENSILE TESTS

In the case of a real tensile test, the spurious waves are less pronounced than in the case of split specimens, since the specimen increases k according to (1) and reduces the magnitude of the reflected waves according to (2) and (3). However, they still can affect the signal that is emitted by the tensile process of the specimen, as shown by the full line in Figure 3 for the example of a tensile specimen made of polyethylen HD-80. Here the stress-strain curve is nearly identical as the one obtained in the case of a split specimen, which means that the actual strength signal is nearly completely overshadowed by the

reflected spurious waves. Although the difference between these two curves is likely to contain information about the tensile behaviour of the specimen, its quantitative evaluation seems to be hardly possible. Furthermore, due to the first reflected tensile wave (peak A) as shown in section 3, a permanent pre-deformation of the specimen, or even its pre-rupture, can be induced before the tensile process itself happens (see section 5).

The situation is better when testing stronger and stiffer materials such as steel. An example of a medium strength steel is shown in Figure 4. The waves that are reflected back into the input bar as discussed in the previous section can be recognized in this case, too. However, as predicted by (2) and (3), the reflected peaks B and A' are of a smaller magnitude than in the case of a split specimen. On the other hand, since the specimen is of higher strength, the signal produced by the tensile process is enhanced. Furthermore, due to the higher E-modulus of the steel specimen, a part of peak A' is not reflected back to the strain gage #1 as A'', but transmitted by the specimen to the output bar, so the reflected spurious peak is further reduced. Therefore, considering the shapes and magnitudes of the relevant waves, the strength signal originating from the tensile test dominates in the strain gage signal C, so the resulting stress-vs.strain curve obtained from this strain history (Fig. 5) is a relatively good approximation of the actual material behaviour. Of course there still is some contribution of peak A'' and B' to the stress signal C of the specimen, but only in a relatively short periode at the beginning of the specimen's elongation process: From the magnitude and shape of the peaks B and A' one can estimate the corresponding contribution to be about 10-20% during about the first three oscillations of the curve.

5. NUMERICAL SIMULATION OF THE TENSILE TEST PROCESS

To investigate the local stress and strain behaviour of a specimen subjected to the loading conditions of a Hopkinson bar tensile test, and to explore the possibilities to simulate dynamic tensile processes numerically, a tensile test of a medium strength steel specimen was modeled by using the finite-difference dynamic code AUTODYN-2D [5]. The whole test set-up (Fig.1) was modeled (all the three bars, the ring and the specimen threaded to the bars), with the computing time beginning at impact of the input bar. The computation results were picked at the connection area of bars/specimen/collar as well as at positions of the two measurement strain-gages on the input and output bars. The behaviour of the tensile specimen and the collar under a compressive wave passing through, followed by the reflected tensile pulse, could be successfully simulated: Fig. 6a shows the stress state at $t=400 \mu\text{s}$, i.e. just after the compressive pulse passed. Since the compressive pulse exceeded the yield stress of the specimen, it left a tensile pre-stress in the specimen and the corresponding compressive stress in the collar. Fig. 6b shows the stress field at about $t=600 \mu\text{s}$, i.e. when the reflected tensile pulse has arrived. At this time, necking has already been initiated, and the contact between the collar and the output bar is lost, so the spurious wave can not be transmitted to the output bar, as discussed in section 3.

6. DISCUSSION AND CONCLUSIONS

It has been shown that the effect of spurious waves on the stress-strain curve is much more pronounced when performing tensile tests than in the case of compressive tests. Since one of the main sources of wave reflection is the air gap between the specimen and the collar (Fig. 1), further Hopkinson bar tensile tests were performed using another (more complicated) type of collar (Fig. 7), which consisted of two halves shaped such that the air gap was minimized. However, compared to the tests with the simple tube-shaped collar, the spurious signals were not much reduced, indicating that this more complicated shape does not increase the stiffness of the collar significantly. It seems, that the spurious reflection waves can not be avoided by optimizing the design of the collar and the specimen.

Since these reflections are always present, they have to be dealt with. The main difficulties actually arise from the fatal coincidence of two spurious reflection waves (peaks A'' and B') and the stress signal originating from the tensile process of the specimen. This coincidence can be avoided by changing some

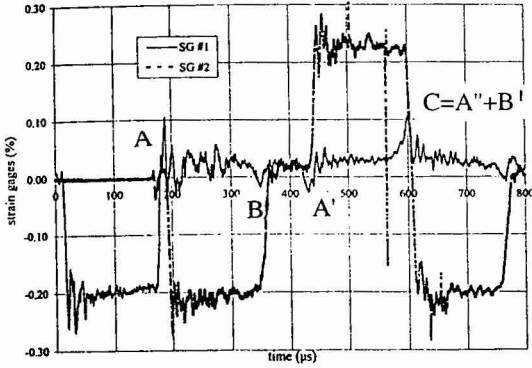


Figure 2: Strain-gages signals registered from Hopkinson bar tensile tests with a cut medium strength steel specimen.

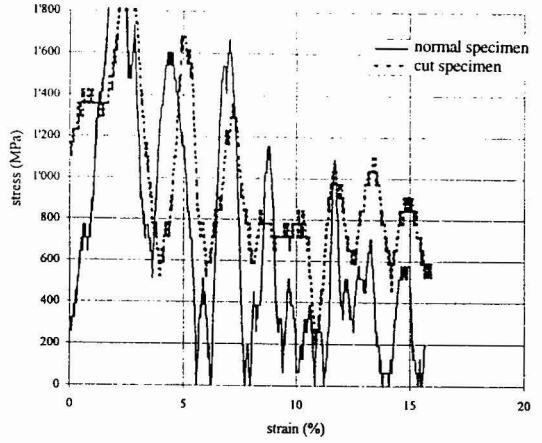


Figure 3: Stress-vs. strain curves obtained from a cut and a normal PE-specimens.

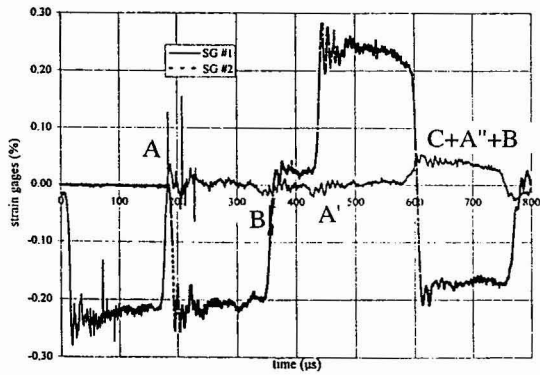


Figure 4: Strain-gages signals registered from Hopkinson bar tensile tests with a normal medium strength steel specimen.

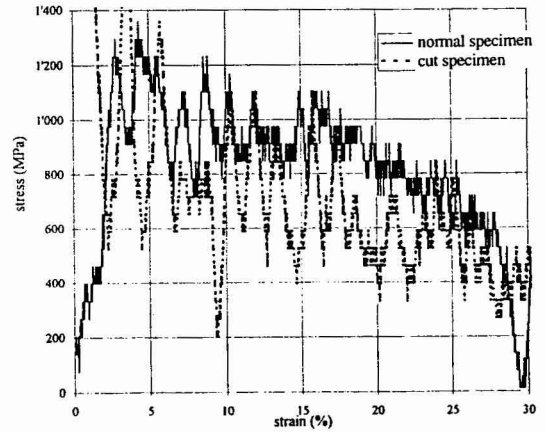


Figure 5: Stress-vs. strain curves obtained from a cut and a normal medium-strength steel specimens.

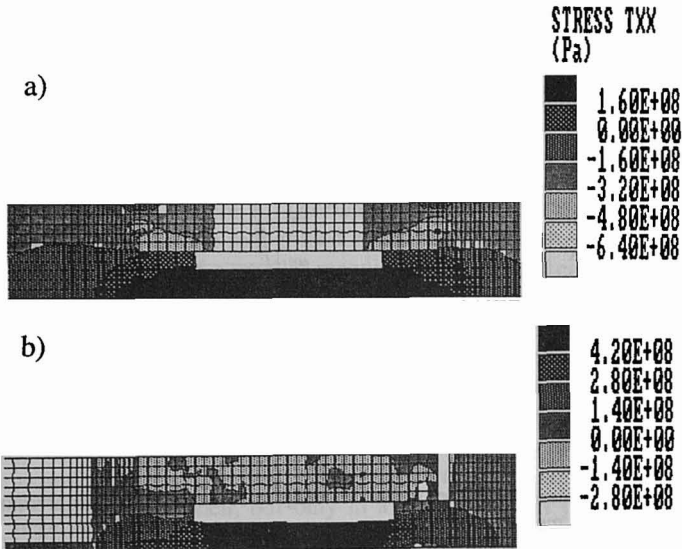


Figure 6: Numerical simulation of the Hopkinson bar tensile test using a collar with medium-strength steel specimen (using the code AUTODYN-2D).

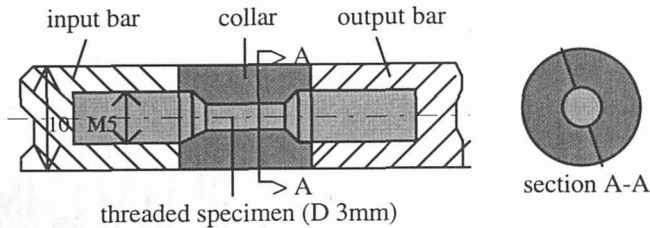


Figure 7: Net-shaped collar (in two halves and with its inside forming closely to the specimen).

geometrical parameters of the set-up shown in Fig. 1, which was optimized for compressive tests, but obviously is unsuitable for tensile tests. The reason for the unfavorable arrival time of peak A" at strain gage #1 is the equality of lengths of the input and output bars. The reason for the coincidence with peak B' is the fact that the distance from the specimen to strain-gage #1 is just equal to the length of the projectile bar. Thus, this coincidence of the main spurious waves A" and B' can be removed from the signal by changing the length of either the input bar or the output bar on one hand, and the location of strain gage #1 or the length of the projectile bar on the other. The corresponding parameters have to be adjusted such that none of the two reflections A" and B' passes strain-gage #1 at the same time interval as the actual stress signal from the tensile process of the specimen.

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