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Structural effects in dynamic testing of brittle materials

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ABSTRACT: Dynamic testing of brittle materials obviously involves the specificities of dynamics and of the special kind of behaviour that describes brittle material. The interaction of both aspects is much more important than for materials like metals which exhibit a plastic behaviour. This interaction is described in the present paper, with a special focus on the Split Hopkinson bar technique commonly used in these fields.

1 INTRODUCTION

So called "brittle materials" first show a brittle behaviour in tension – sometimes in simple compression – and usually a plastic-like behaviour under confined compression. This plastic-like behaviour is more often the response of a damaged material that does not recover its integrity after unloading. It then appears that the notion of behaviour, when applied to brittle materials, is strongly dependant on the loading. It is also dependant on the size of the elementary element in which it will be introduced for the (FEM) modeling of a real structure. Basic physical phenomena may involve a very small scale while a much large scale is required for modeling.

The same situation occurs in the case of testing when, in the opposite way of thinking, one has to go from global measurements to stress-strain relations. Accounting for structural effects in testing is then an evidence as any specimen tested is nothing else than a structure. It will appear in an evident manner for many tests used in brittle material testing (like flexion tests for instance), especially for concrete often requiring big specimens (in "10 cm" range, minimum).

For this reason, we will especially focus on tests for which this aspect does not clearly appear as simple compression and tension tests that are safely processed in a standard way in the case of metals.

In quasi-static testing, going from global measurements – force, displacement, gauge measurement – to the stress-strain relations requires the homogeneity of mechanical fields within the tested area, basically the strain field. Such an assumption cannot exactly be verified in dynamic testing, especially with brittle materials generally described in the range of small strains. This leads to specific approaches that are investigated in the present paper.

This idea can be simply quantified, following Forquin (2013). Considering for example the case of HS-Concrete (High performance) in compression, at an average strain rate of 100/s (rather small in dynamics) it would take 10 µs to reach the failure strain of 0.1%. In order to assume equilibrium, waves should run at least 5 round-trips within the specimen during this time, corresponding to a distance of 4 cm (if the speed of wave is 4000 m/s) leading to a maximum specimen size of 0.4 cm which could not be, in any case, representative of the material.

The larger the representative size, the smaller the failure strain, the more difficult dynamic testing.

Table 1. Mechanical properties of common brittle materials from Forquin (2013),

Materials:	Glass	S-SiC ceramic	Limestone rock	UHS-Concrete	HS-Concrete
Tensile strength (σ_t): Elastic failure strain (σ_t/E): Inelastic tensile failure strain (ε_t^{in}):	~ 50 MPa **~ 0.1%** 0	~ 400 MPa **~ 0.1%** 0	~ 25 MPa ~ **0.03%** 0	~ 20 MPa ~ **0.04%** 0	~ 5 MPa ~ **0.01%** ~ 0.02%
Compressive strength (σ_c): Elastic failure strain (σ_c/E): Inelastic compressive failure strain:	-	~ 6000 MPa **~ 1.5%** 0	~ 150 MPa ~ **0.2%** 0	~ 200 MPa ~ **0.2%** 0	~ 40 MPa ~ **0.1%** ~ 0.2%
Yield stress (Hugoniot Elastic Limit):	~ 4000 MPa	~ 12 GPa	-	-	~ 350 MPa
Toughness (K_I^C):	~ 1 MPa√m	~ 3.2 MPa√m	~ 2 MPa√m	~ 1.6 MPa√m	~ 2 MPa√m
Size of microstructure	< nm	2-5 µm	0.1 mm	0.2-0.5 mm	2-5 mm

1.1 *Meaning of the word "dynamic"*

As distinct from the term "static", "dynamic" implies the influence of time. A test is said to be "quasi-static" – while a purely static test cannot exist – when the effects of time can be neglected. For any real test, the effects of time are typically expressed in two ways:
- by inertia forces resulting from the non null acceleration to which elements of structures are submitted.
- by the behaviour of each elementary volume of the material depending on evolution in time of the elementary mechanical values (stress and strain) and possibly of their time derivatives. This dependence is described by the generic name of viscosity.

This distinction is strictly linked to the notion of elementary volume underlying the definition of the behaviour. Actually, the fact that viscosity effects can be the manifestation of inertial microscopic phenomena cannot be excluded.

The behaviour that experimentalists are looking for, to be used in modeling, is supposed to refer to any elementary volume of the studied material free of internal forces.

1.2 *Specificity of dynamic testing arrangements*

The first difficulties encountered in dynamic testing are linked to transient effects inside the machine and the associated sensors: the balancing time of the machine and its sensor array (elastic waves moving back and forth) could be not negligible relative to the length of the test. It has also to be taken care that the acquisition frequency is far higher than the frequency of the transient signals to avoid a possible degradation of the results. Such difficulties mainly concern the faster side of machines providing a range of speeds starting from quasi-static to dynamic loadings.

The response of the machine will be briefly investigated in the special case of SHPB (Split Hopkinson Pressure Bars), as matter of illustration, as it is common knowledge that Hopkinson bars have been indeed especially designed to deal with waves and provide reliable measurements at specimen boundaries.

1.3 *From global testing to material behaviour.*

Recall that the homogeneity of mechanical fields is required in order to derive in a simple way the stress-strain relations from global measurements. This homogeneity depends on the specimen dimensions in regard of the representative size of the material tested. Transient effects in the specimen due to the finite speed of waves lead to non homogeneous stress and strain fields in an increasing manner with the specimen size (as quantified above). The homogeneity also depends on boundary conditions, as for instance friction at specimen ends in 1-D compres-

sion testing. And, last but not least for materials investigated here, it depends on the material behaviour as, for instance, a softening behaviour is supposed to induce localization.

When dealing with brittle materials, especially with concrete, the representative size must be large in comparison with the size of testing devices. This size factor also gives an increased importance to structural forces induced by inertia effects that appear most often in addition to loading forces.

2 AVAILABLE TESTS AND MEASUREMENTS

It would not be possible to give an extensive list of dynamic tests used for the experimental study of brittle materials. Our paper will then be restricted to the more common ones, with a special attention to those which are more familiar to the author.

Looking for the dynamic material behaviour under compression, SHPB is commonly used (strain-rates ranging from 50 to 500 for concrete). Under such a loading, brittle material are very sensitive to lateral pressure (as shown for instance in fFigure. 1) so that three (complementary) loadings are found: simple compression, compression under controlled pressure, compression of a confined specimen preventing lateral expansion.

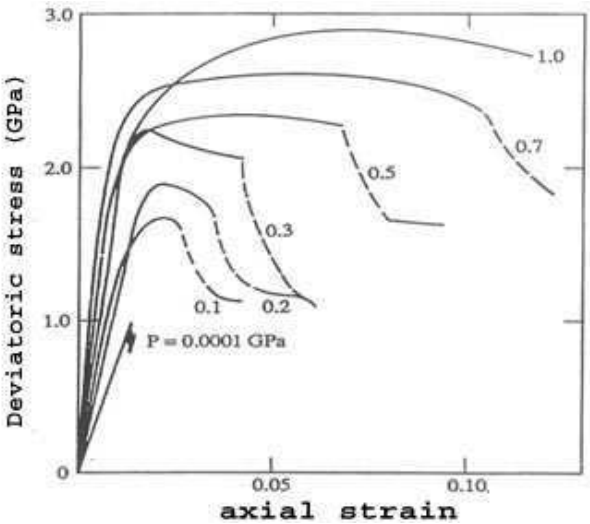

Figure 1. Tri-axial quasi-static compression of a ceramic, from Heard & Cline (1980).

The direct impact test could also be used but it is not well adapted as its processing requires the assumption of equilibrium. At higher strain rates, plate-plate impact tests have been used, but it is shown that they do not provide a direct access to the behaviour and they are limited to very high strain rates ($> 10^5 s^{-1}$)

For tension testing, the two more direct approaches are the (modified) SHB for direct tension and spall tests. These last ones, as they start with a compression phase, cannot afford to avoid a transient analysis.

Other tests leading to fracture in tension involve a clear structural response without homogeneity of mechanical fields: Brazilian test, flexion of beams or plates.

3 COMPRESSION

3.1 *Compression with SHPB.*

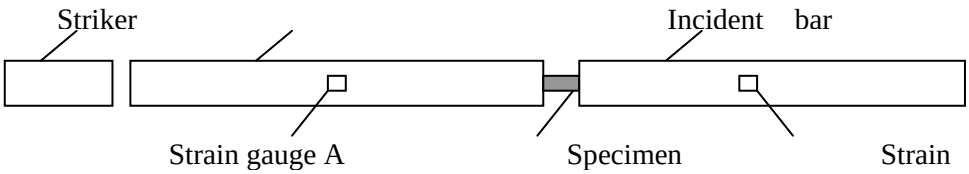

Figure 2. Typical SHPB set-up.

3.1.1 *Basics of the machine*

SHPB suffers from its historical original use introduced by Kolsky (1949). He proposed his formulas before computers had become generally available for data processing. He used identical input and output bars (same length, diameter and material) and put strain gauges at the middle of each bar. Neglecting the dispersion in the bars and assuming quasi-static equilibrium, Kolsky derived:

$$\varepsilon_i(t) + \varepsilon_r(t) \cong \varepsilon_t(t) \quad (1)$$

with ε_i, ε_r and ε_t the incident, reflected and transmitted strains as recorded at the gauges.

The average strain ε_s of the specimen is given by

$$\varepsilon_s(t)=\int_0^t \dot{\varepsilon}_s(\tau)d\tau=-\frac{2c_b}{l_s}\int_0 \varepsilon_r(\tau)d\tau \quad (2)$$

with c_b the speed of waves in bars, l_s the specimen length.

The average stress σ_s is obtained from the output force (or from the average of input and output forces which provides the same value within the hypothesis of quasi-static equilibrium).

$$\sigma_s(t)=\frac{A_b}{A_s}E_b\varepsilon_t(t) \quad (3)$$

with A_b and A_s the areas of the bars and the specimen, respectively, E_b Young's modulus of the bars.

As soon as the hypothesis of quasi-static equilibrium is not verified, as it is the case for most compression tests on brittle materials, this analysis is not valid.

One has then to go back to basic measurements provided by SHPB. For sake of simplicity, following most authors, we consider identical bars. It does not restrict the generality of the presentation. Considering the values of the strain in bars at specimen ends, forces and displacements at both specimen ends are given by formulas Formulas (4,) and (5)

$$v_i=-c_b(\varepsilon_i-\varepsilon_r) \qquad v_o=-c_b(\varepsilon_t) \quad (4)$$

$$F_i=A_bE_b(\varepsilon_i+\varepsilon_r) \qquad F_o=A_bE_b\varepsilon_t \quad (5)$$

where v_i, v_o, F_i, F_o are input and output speeds and input and output forces at specimen faces, respectively. ε_i, ε_r, ε_t are incident, reflected and transmitted waves, respectively, computed at specimen faces.

When the specimen diameter is less than half of that of the bars, the displacement deduced from speeds (4) is overestimated and must be corrected, especially in the case small strains – see Safa & Gary (2010).

The measurement finishes here. In other words, equations Equations (2) and (3) are not direct measurements. They are (only) derived from (4) and (5) on the basis of the hypothesis of quasi-static loading.

3.1.2 *Wave shifting. A precise method for SHPB.*

The 1-D analysis of the waves implicitly takes account of the Saint-Venant principle: a certain distance is needed between the end of the bar and the strain gauge to insure the homogeneity of the strain across the bar (typically 5 diameters). The three waves ε_i, ε_r, ε_t involved in for-

mulas (4) and (5) being that at specimen faces, one has to take care of the precise shifting in time from gauges to bars ends.

One needs then to use a wave theory to deduce the strain (as it would be if this point was not an end) at the end a bar. This shifting involves two aspects:

- One is to account for wave dispersion (this is a 3-D effect that is usually modeled in 1-D. The variations of mechanical parameters along the radius of bars are indeed very small at low frequencies involved in standard tests as shown by Davies (1948) and Merle & Zhao (2006).
- The other is to correct possible errors in the distance from the gauge to the bar end, or for an imprecise wave speed, or more generally to correct for an imperfect contact between the specimen end and the bar. Note that, with an input speed of 5 m/s, an 0.2 mm thick imperfection induces a 40 µs delay between the first touch and the perfect contact with a 5 m/s input speed.

The input force being proportional to the sum of the incident and reflected waves, it is clear that a relative imperfect shifting in time would induce an error, especially at the beginning of the loading. For an improved shifting, one can use a method, introduced by Zhao & Gary (1996). It is based on the transient simulation of an initial elastic behaviour of the specimen. The incident wave at the input specimen face been known after the dispersion correction process, reflected and transmitted waves can be computed – depending on specimen dimensions, bar dimensions and mechanical properties, specimen Young's modulus. The only unknown is the last one. Using a try and error method, one rapidly finds the Young's modulus that gives shapes of both simulated transmitted and reflected waves similar to those known at the input and output specimen faces. This operation does not work correctly if the dispersion is not taken into account, even with elastic bars, because the elastic response of the specimen concerns the first instants of the loading where the rising time of the waves is strongly affected by the dispersion. An illustration of the method is presented in Ffigures 3-4.

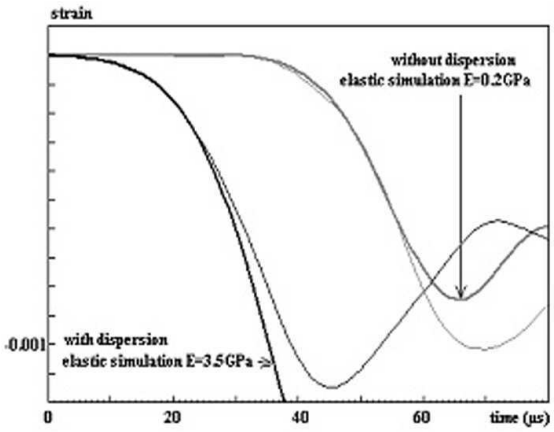

Figure 3. Elastic simulation of the output wave, with and without dispersion correction.

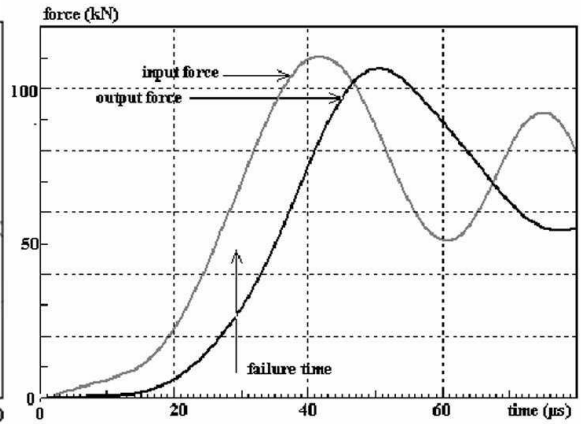

Figure 4. Input and output forces.

Figure 3 shows that the "best" Young modulus fitting the output wave is not realistic at all (0.2 GPa) when dispersion correction is not applied. Furthermore, transmitted and reflected waves cannot be simultaneously fitted. On the contrary, the realistic value of 3.5 Gpa induces a good fitting when dispersion correction is applied, for both reflected and transmitted waves. Furthermore, the separation between the elastic simulated wave and the measured one gives the instant when the specimen starts to have a non elastic response – failure time for a purely elastic material. In the present case, it is around 30 µs.

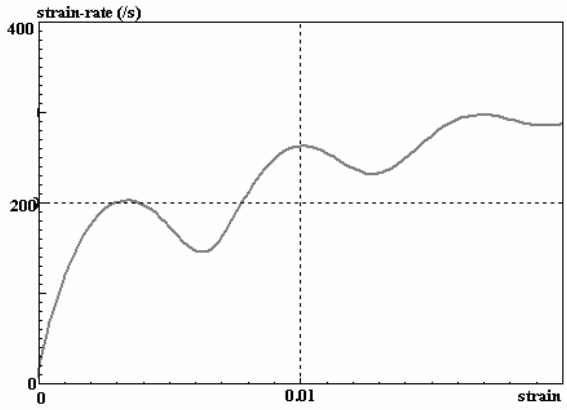

Figure 5. Measured average strain rate.

Looking at Ffigure 4, one sees that fracture initiates a long time before equilibrium is reached. Standard SHPB formulas cannot be used to derive the behaviour. Consequently, input and output forces, together with input and output speeds (not shown here) should be the basis of the subsequent analysis towards the behaviour.

Furthermore, the average strain rate varies very rapidly with the strain (as seen in fFigure. 5) so that associating a behaviour to a known strain-rate would not have a clear meaning.

3.1.3 *An example for a transient analysis for brittle materials*

On the basis of force and velocities measurements at specimen faces, an approach of the specimen behaviour based on an inverse method is theoretically possible, as shown by Rota (1994), as these four values are superabundant measurements.

If an appropriate form of the material behaviour with some parameters to be determined is known, using a part of data (two velocities, for example) as input data, another part of data (the two forces) associated with the given parameters can be calculated. The best set of parameter which gives the calculated forces well in agreement with the measured ones can theoretically be found.

An example of a 1-D analysis based on such a method is shown in Ffigure 6, from Gary & Zhao, (1996). It shows that both input and output forces can be recovered.

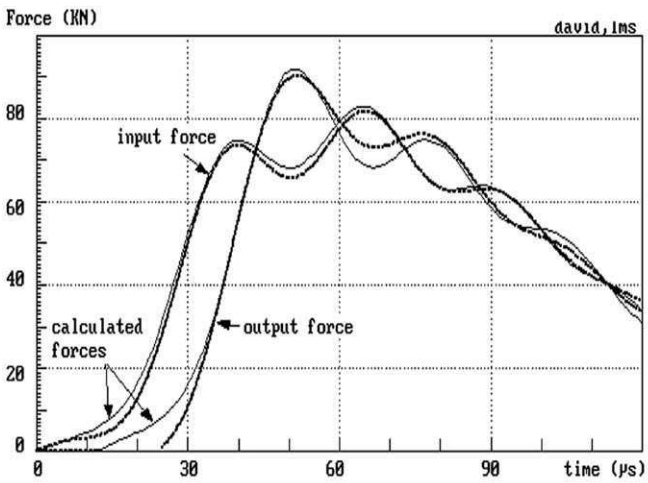

Figure 6. Simulated and measured forces for a test on concrete.

The model used for this simulation helps for the understanding of axial transient effects but, being one-dimensional, it could not account for the increase in strength that could be due to lateral inertia effects. Accounting for this effect would need to make all the parameters of the model strain-rate dependant.

3.1.4 *Influence of strain-rate on the apparent strength of concrete.*

3.1.4

Many dynamic tests in simple compression show a sharp increase in strength with strain rate, as shown in the famous figure presented by Bischoff and Perry (1991), here Ffigure 7.

This important effect have has been proved to be purely structural, as explained underneath. It is due to the change of behaviour induced by an artificial lateral pressure, itself the results of lateral inertia of the specimen preventing its expansion.

This effect is also observed for metals when the apparent plastic response is increased by the tri-axial state of stress induced by inertia. In only leads to a small correction for standard metals, especially because the specimen tested are usually small. Formulas established in this case – for instance by Malinowsky & Klepaczko (1986) show that this effect increases with the square of the specimen radius, the axial strain-rate, the time derivative of the axial strain-rate, and the mass density of the material. The greater importance of the spherical behaviour on the response of brittle materials makes this effect more dramatic in our case. When concrete is concerned, as seen in Ffigure 7, the representative size of the material requires big specimens (at least a few centimeters in length and diameter). The figure shows that the sudden increase can appear in a range of 1 decade, between 10 and $100s^{-1}$.

The case of ceramics. This structural effect being strongly sensitive to the specimen size, testing smaller ceramic specimens in compression would delay this effect towards higher strain rates. Note that these materials being very hard, they induce a special testing difficulty, as they can show an elastic limit higher than that of the bars. When the behaviour is almost perfectly elastic-brittle, there is a huge influence of local imperfections at specimen faces that can induce local stresses much higher than the average measured one, giving an underestimated resistance of the material. For both previous difficulties, a solution is to use dog-bone specimens which need a special processing. Provided that the larger part of the specimen remains elastic, this special processing is possible.

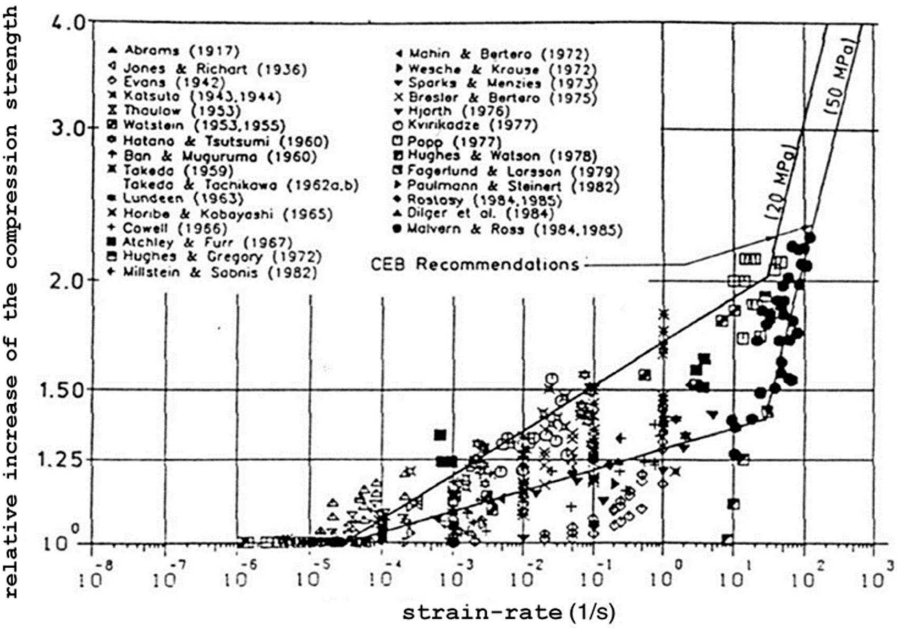

Figure 7. Influence of strain-rate on the apparent increase of the strength of concrete with strain rate.

3.2 *Compression with SHPB under controlled lateral pressure.*

A method proposed by Gary & Bailly (1998) is briefly recalled here. Following Christensen et al. (1972) and Malvern et al. (1991), the specimen is introduced into a cylindrical quasi-static

pressure cell. The bars are acting as pistons and are introduced in the cell through seal rings. A scheme of the complete set-up is shown in fFigure 8. The lateral pressure can be applied with oil (up to 50 MPa), or with air (up to 10 MPa).

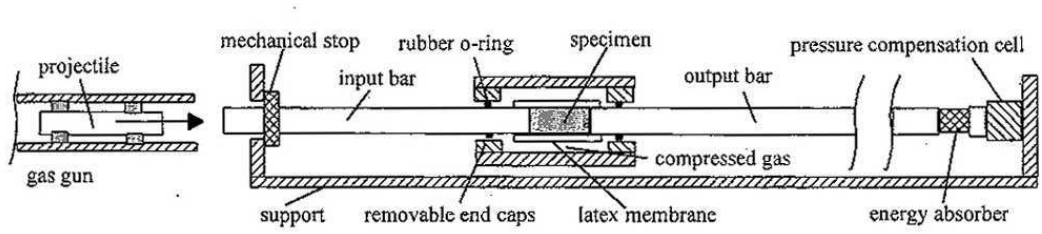

Figure 8. Set-up for confined pressure tests.

3.2.1 *Sealing problems*

Using a significant lateral pressure of oil (20 MPa) a test without specimen (bar against bar) has been performed to investigate the influence of seals on waves propagating in the bars. Input and output forces have been calculated (Ffigure. 9). They are not very different, and it proves that the influence of seals can be disregarded.

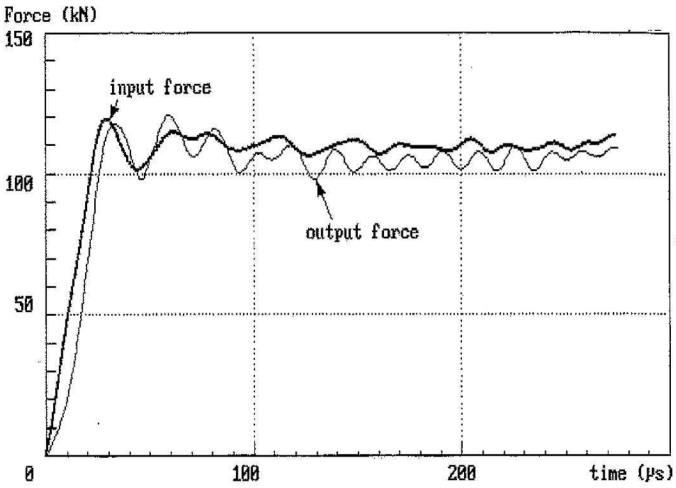

Figure 9. Input and Output forces for a confined test without specimen.

3.2.2 *Lateral pressure*

It seems reasonable to assume that a static confined pressure applied with air will not be significantly affected by the increase in the diameter of the specimen induced by the deformation (in this device, the chamber is 120 mm long and has a diameter of 75 mm so that with a 40 mm long and 40 mm diameter specimen, the volume of the fluid in the chamber is almost 10 times the volume of the specimen).

The situation is not so clear with oil and it is not sure, because of transient effects in the fluid, that a measurement of the oil pressure during the test at a point in the chamber would give an exact measure of the pressure applied to the specimen. To evaluate this question, tests with oil and with air have been performed, using the same initial confinement pressure and other initial conditions. Results under oil pressure look very much like the ones presented in Malvern et& al,. (1991) using a very similar device where water lateral pressure was used. When lateral pressure is applied with air, the stress strain relation shows a much lower apparent strain hardening, as presented in Ffigure 10.

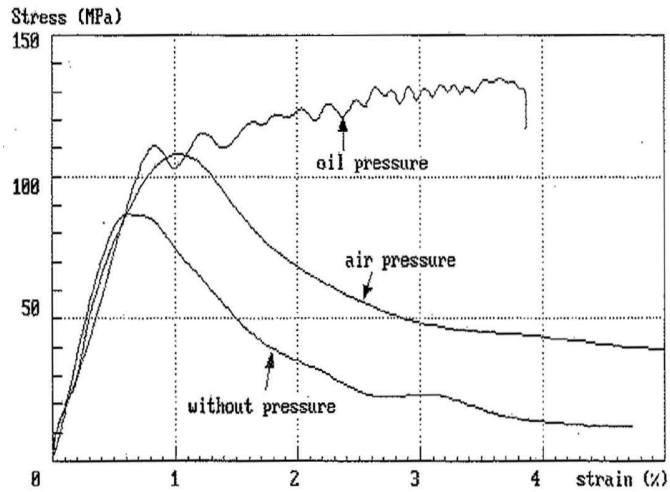

Figure 10. Comparison between different lateral loading conditions.

The structural effect clearly appears here. Axial compression induces an expansion of the specimen due to its non null Poisson's ratio. The weakest response, which is also the more brittle, is obtained without confinement – case of § 2.1. With air pressure (20 MPa), a significant increase of the maximum stress appears, but the same kind of behaviour is observed. This evolution can be explained with a model proposed by Gary & Bailly (1998), briefly recalled in Ffigure 11, inspired from the real breaking process of concrete under compression, introducing lateral inertia and lateral pressure.

With oil pressure, inertia of oil presumably prevents the lateral expansion of the specimen, (so that the lateral pressure increases in the vicinity of the specimen) leading to a loading closer to that obtained with oedometric tests (described in § 2.3)

Note that, since 1998, more sophisticated models have been developed based on a physical approach – (Desnoual et al. (1997) – accounting in a quantified way related to a Weibull (1939) analysis for the nucleation of cracks and their propagation. Extended to dynamic loading by Forquin & Hild (2010) where the finite speed of crack propagation is introduced – this aspect clearly missing in the model of Ffigure 11 – , they account for most structural effects observed in uniaxial compression in particular and in many other dynamic loadings.

Going back to fFigure 11, it is easy to understand that lateral inertia will also prevent, or at least delay, the specimen expansion under pure compression. It explains the apparent increase in strength with average strain rate observed for uniaxial compression tests.

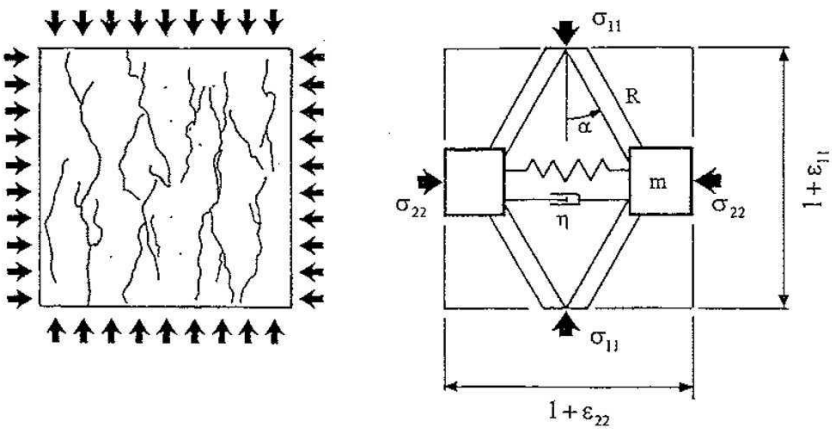

Figure 11. Analogical rheological model for an elementary volume of concrete.

3.3 *Simple dynamic compression without lateral expansion.*

It is guessed from Ffigure 10 that axial compression without a significant lateral expansion (oedometric loading) does not show a brittle behaviour as a global strain-hardening is observed, preventing localization. Very high stresses can be reached under such a loading, presumably breaking the micro-structure when it is associated with high strains. The involved behaviour is then not anymore that of the initial material before loading but it is appropriate to describe its evolution under this kind of state of stress. Such situations are found in military applications or in studies connected with the safety of buildings (power plants) regarding an accidental internal loading or external loading (plane crash). Such tests have been developed in the quasi static regime. Because of high pressure involved, and the huge elastic energy stored in the machine, they have to be done in special buildings, for safety reasons, and are expensive.

At some points of view, the corresponding dynamic test is easier as the energy involved is dissipated in a very short time. Such a test has been developed in our laboratory by Forquin et al. (2008) . The specimen is confined in an instrumented metallic ring and loaded by means of a SHPB especially designed for this purpose, with steel bars 80 mm in diameter. The cylindrical specimen embedded in a steel confinement ring is compressed using 2 cylindrical plugs (Ffig.ure 12). The concrete specimen is 30 mm in diameter and 40 mm long. The steel plugs have the same diameter and a thickness of 10 mm. The steel ring has an outer diameter of 65 mm and is 45 mm long. A special interface product ensures that the expansion of the ring is due to internal pressure, allowing for the measurement of the confinement pressure.

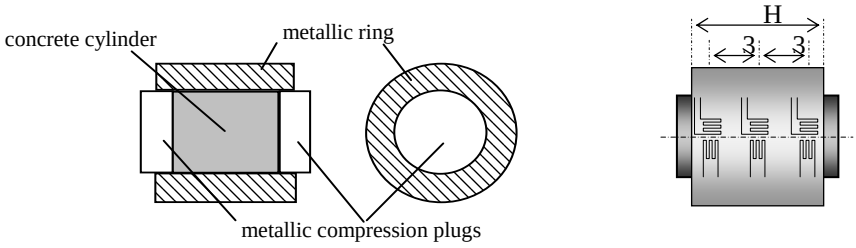

Figure 12. Cylindrical specimen embedded in a steel ring.

The typical axial force-displacement response shows a positive strain hardening (as seen in Ffigure. 13). It is then expected that an acceptable homogeneous state of stress and strain is obtained in the specimen. Deriving the average stress from the output force should be then a valid approximation.

Simultaneous gauge measurements made on the elastic ring allow for an evaluation of the radial stress and, consequently, of the lateral pressure applied to the specimen. Furthermore, the radial expansion leading to inertia effects being prevented by the ring, one may think that structural effects can be neglected in such a test.

This is not exactly the case as one has to take care of two secondary structural effects. One is the contribution to the axial force of the friction between the ring and the specimen. An other is the difference between forces measured at bar ends and required forces at specimen faces. These points have been carefully studied in (Safa, 2008) where explicit formulas can be found to derive friction and lateral pressure from gauges measurements.

Figure 14 show the difference between forces at bar ends and forces at specimen ends as deduced from a transient analysis of the response of the plugs.

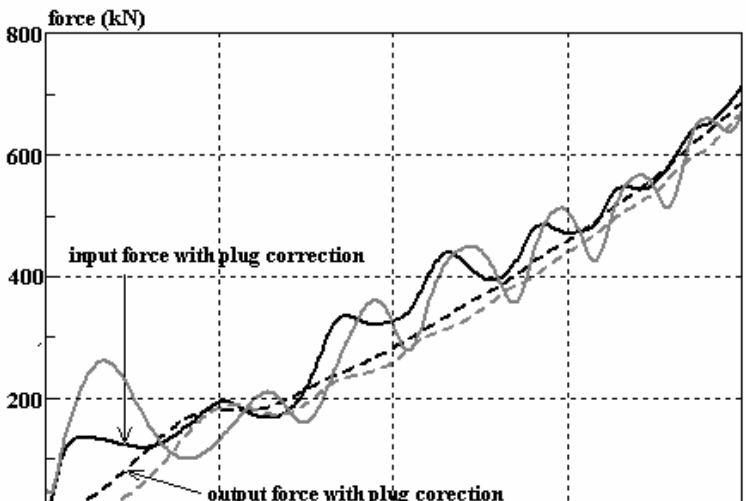

Figure 13. The difference between forces at bar ends and at specimen ends.

The main result obtained with this test – (Forquin, et al. (2010) – is that the material response is very sensitive to the presence of free water, concerning both deviatoric and hydrostatic behaviours. A constant bulk modulus is observed for dried concretes whereas the corresponding hydrostatic behaviour of saturated specimens is non-linear. Moreover, dried concretes show a strong increase of the strength with the loading speed whereas water-saturated specimens exhibit an almost-perfect saturation of the strength. It appears that, supposedly by reducing the level of effective stress applied to the skeleton, the pore-pressure inside the concrete strongly influences the dynamic behaviour of confined concrete.

3.4 *Very High strain-rates and 1-D (compression) strain. Slab-plates tests.*

In the standard case (– Zukas (1982) –, loading is caused by the impact of two identical plates. The impact speed V_0 is known. On the fixed slab, a rear face rate measurement (usually made using laser interferometers) is conducted. The shock induces a plane shock wave propagating at a velocity *D*. Discontinuities of material rate *u*, pressure *P*, the volumic mass or mass volume *V* and inner energy *E* are associated with this wave. Assuming the initial conditions are zero, it can be inferred from the Rankine-Hugoniot conservation equations that:

$$V = V_0(D-u)/D\,, \qquad P = Du/V_0\,, \qquad E = E_0 + P/2(V_0 - V) \tag{16}$$

At the time the shock is known, measuring the rear face speed allows to locate the moment when the wave arrives, to measure *D* and calculate *u*. Then the test enables to establish a relation between *P* and *V* (and also between *D* and *u*) giving one point of the so-called “shock polar curve”. In order to deduce a uniaxial stress-strain curve one has to make some hypothesis on the behaviour model of the material. In that sense, the structural effect is, in this test, evident. The usual assumption used for metals, neglecting elasticity, that the behaviour is purely deviatoric (without any volume variation) is not valid for brittle materials. The test should then be processed by an inverse method.

4 TENSION

4.1 *Tension with SHB.*

Following the same basic ideas than in compression, dynamic tension tests for concrete have been developed with Hopkinson bars – (Reinhardt (1982). Referring to Ttable 1, the limits induced by the very small facture strain do not allow for homogeneity of the mechanical parameters at strain-rates greater than $10s^{-1}$, which is hardly in the dynamic range. Furthermore, the specimen holding is difficult, generally requiring the use of glue in the best case, which makes the global measurements unprecise. At lower strain rates, it is then safe to use complementary measurements, with strain gauges for instance.

For all these reasons, the most commonly used method to investigate the dynamic behaviour in tension is the spall test.

4.2 *Spall test.*

Spall tests have been previously introduced for metal and plate-plate impact tests to measure the tension strength (under uniaxial strain) at very high strain rates. In order to avoid gripping problems, the spall test has been introduced (under uniaxial stress) to measure the tension strength of brittle materials, and concrete in particular – (Klepaczko & Brara (2001).

This smart method is based on the fact that brittle materials have a higher strength in compression than in tension and that they remain in the elastic range in compression. A sketch of the test is given in Ffigure 14.

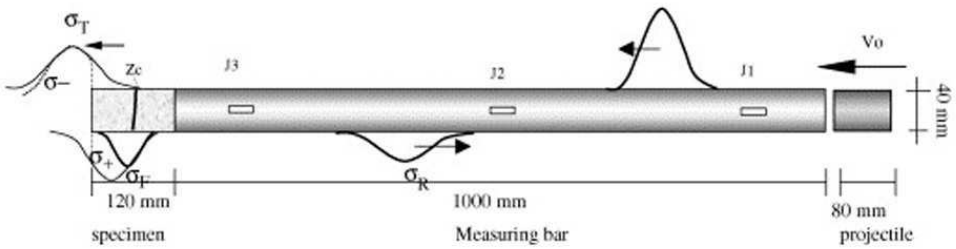

Figure 14. A sketch of the spall test, from Klepaczko & Brara (2001).

Using a long thin specimen, a known compression wave is induced at one end. When it reflects at the free other end, a tension wave is produced such that the stress at the free end remains null. If the initial pulse is short enough, a state of tension is induced in the specimen at a certain distance of the free end. If the stress is greater than the material strength in tension, the specimen brakes.

It is very clear, at this stage, that there is no possible direct measurement of the fracture stress. The analysis of the test is indeed based on the previous knowledge of the behaviour. The standard method assumes that the material remains elastic in compression and in tension when the stress is under the fracture stress. Using a 1-D analysis of the waves (where dispersion can be introduced) and knowing the position of the (first) fracture on can go back to the failure strength. Some authors use a measurement of the rear face of the specimen, and the formula (17) established by Novikov (1966), see Ffigure 15.

$$\sigma_{spall} = 0.5 c_0 \Delta v \tag{17}$$

Both analyses are based on a pure 1-D elastic response of the material until fracture. In that sense, this test evidently involves structural aspects. The method cannot account for damage occurring before fracture.

A new method based on image correlation and using the principle of virtual work has been recently developed – (Pierron & Forquin (2012). It only works in the dynamic range and needs a fast speed camera but can provide a local measurement (on the surface of the specimen) of the stress and associated strain.

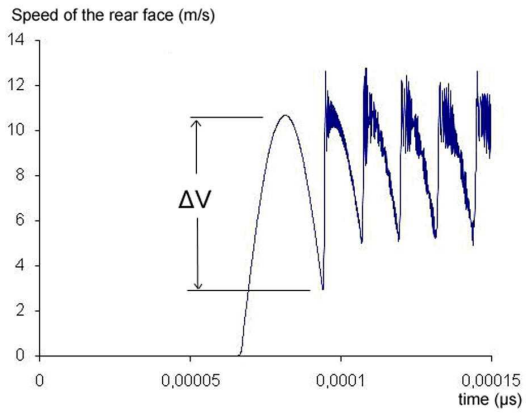

Figure 15. Rear face speed measurement (Novikov, formula 17)

4.3 *Other tension tests..*

Other tension tests that clearly involve structural effects will only be briefly mentioned as the structural response of the specimen is the basis of the processing.

Like in the case of spall tests, their analysis needs assumptions on the material behaviour. The simplest one is the 1-D elastic-brittle behaviour. More complex behaviours can be investigated provided that experimental data are sufficient and precise enough to support inverse methods – see also Erzar & Forquin (2011).

4.3.1 *The Brazilian test.*

We consider a cylinder compressed perpendicularly along two diametric generators. A quasi-static plane strain elastic calculation shows that a constant tension maximum stress is induced in the central plane defined by both previous generators. Achieving quasi-static conditions and punctual contact loading is difficult so that, when compression is applied with SHPB, it is better to carry out a numerical calculation, even with an elastic brittle material – (Tedesco et al. (1993).

4.3.2 *The flexion test.*

A dynamic flexion test may be conducted with a SHPB with three bars. The output bars support a beam loaded in his middle by the incident bar – (Delvare et al. (2010). An explicit analysis of the elastic dynamic response of the beam allows for the calculation of the reflected wave from the knowledge of the incident one. It is then assumed that the instant when the real reflected wave separates form the simulated one corresponds to the fracture of the beam. The principle of the method is similar to that described in 3.1.2.

4.3.3 *Shock tube test on plates.*

The principle is to load the specimen using a shock-tube (as seen in Ffig.ure16). Such a device uses a tube as a wave guide where the loading can be generated by a well-controlled air-shock wave – see for example Toutlemonde et al. (1993). A well known pulse pressure of a given amplitude and duration is applied at one specimen face, allowing for precise initial data for an inverse calculation. The response of the structure is observed with extra sensors (gauges, velocity and displacement measurements).

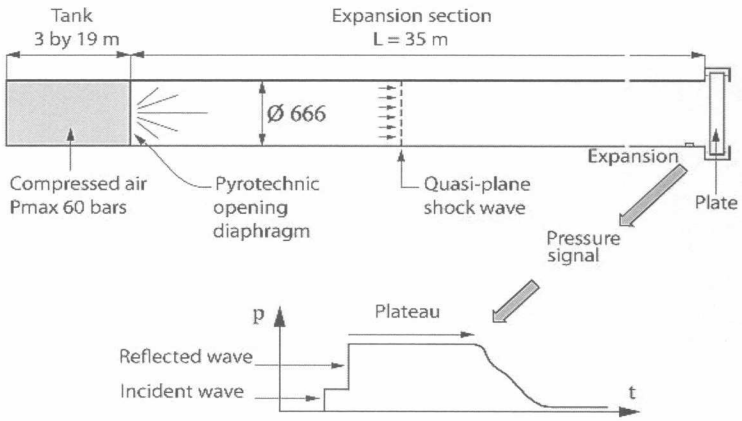

Figure 16. Sketch diagram of the shock-tube test from Toutlemonde et al. (1993)

5 CONCLUSION

Dynamic testing theoretically cannot provide direct stress-strain relations as transient effects prevent for a homogenous state of stress and strains in the specimen. In order to investigate the strain-rate effects on the material behaviour, that can be significant at low strain-rates, some techniques (like SHPB) use the assumption of a valid equilibrium. The quality of this assumption can be estimated by comparing the duration of the test with the time to equilibrium quantified by the transfer time of the waves through the specimen. As the wave speed is a constant of the material, this time increases with the specimen size, making more difficult the testing of large specimens as required for instance for concrete.

We have seen that this question is especially critical for most brittle materials the behaviour of which in tension is only meaningful at small strains. Consequently, a careful processing, accounting for all measurements – for instance both input and output forces in the case of SHPB – must not be avoided. A pleasant point is that, mainly because of small strains, the temperature increase of the specimen – dynamic tests being adiabatic – can be neglected.

In the special case of simple compression, lateral inertia effects can induce a confinement stress that has a strong influence on the axial response of the specimen and should not be forgotten. The nice thing with this confinement, even more when it is under control with a cylindrical cell, is that the behaviour shows a positive strain hardening making easier the processing of the test.

Assuming the theoretical elastic-brittle behaviour in tension, pure structural tests have been developed (flexion, spall, Brazilian) that directly provide a tension strength. One must keep in mind that the corresponding analysis is not valid as soon as the behaviour is non-linear or shows damage, and that transversal 3-D effects are not taken into account.

These methods are still of interest for a first approach of the material behaviour but they should be validated by inverse methods, in other words by direct calculations – with an adequate model, which is not the less difficult problem – of the measured response of structures submitted to a known loading.

For brittle materials, more than for metals, redundant measurements should be the first basis of a reliable testing.

REFERENCES

Bischoff, P.H. & Perry S. H., 1991., Compressive behaviour of concrete at high strain rates,. *Materials and Structures*, November 1991, Volume 24, Issue(6):, pp 425-450.

Christensen, R.J., Swansow S.R., Brown W.S., 1972. Split Hopkinson bar test on rock under confining pressure. *Experimental Mechanics*, 12:, 508-41.

Davies, R.M. ,1948., A critical study of Hopkinson pressure bar. *Phil. Trans. Roy. Soc*., A240:, 375-457.

Delvare, F., Hanus, J.L., Bailly, 2010, P. 2010. A non equilibrium approach to processing Hopkinson Bars bending test data:application to quasi-brittle materials, *Int. J. of Impact Engng*., Vol. 37, Issue (12):, pp. 1170–1179.

Denoual, C., Barbier, G., Hild, F. ,1997,. A Probabilistic Approach for Fragmentation of Ceramics under Impact Loading. *C. R. Acad. Sci*. Paris IIb 325,: 685-691.

Erzar, B. & Forquin, P., 2011., Experiments and mesoscopic modelling of dynamic testing of concrete,. *Mechanics of Materials*, 43, pp. : 505–527.

Forquin, P., Gary, G., Gatuingt, F., 2008., A testing technique for concrete under confinement at high rates of strain., *International Journal of Impact Engineering* 35:, 425–446.

Forquin, P. & Hild, F., 2010., A probabilistic damage model of the dynamic fragmentation process in brittle materials,. *Advances in Applied Mech*, 44, pp.: 1-72. Academic Press, San Diego, CA

Forquin, P., Safa, K., Gary, G., 2010,. Influence of free water on the quasi-static and dynamic strength of concrete in confined compression tests,. *Cement and Concrete Research*, 40:, 321–333.

Forquin, P. 2013,. *cConference 24-1*, LMS, Ecole Polytechnique, France.

Gary, G. & Zhao, H., 1996.. Measurements of the dynamic behaviour of concrete under impact loading,. *proceedings of 2nd ISIE'96*, Beijing, China.

Gary, G. & Bailly, P., 1998,. Behaviour of a quasi-brittle material at high strain rate. Experiment and modelling,. *European Journal of Mechanics, A/solids*, 17, n°(3,): 403-420.

Heard, H., C. & Cline, C., F., 1980,. Mechanical behaviour of polycrystalline BeO, Al2O3 and AlN at high pressure., *Journal of Materials Science*, August 1980, Volume 15, Issue (8,): pp 1889-1897.

Klepaczko J. R. & Brara A., 2001,) .An experimental method for dynamic tensile testing of concrete by spalling . *International Journal .of Impact Engineering* 25, pp.: 387-409.

Kolsky, H., 1949. An investigation of the mechanical properties of materials at very high rates of loading.. *Proc Phys Soc (London)* 63,: 676-700.

Malinowski, J.,.Z. & Klepaczko, J.,R., 1986,. A unified analytic and numerical approach to specimen behaviour in the Split-Hopkinson pressure bar,. *International Journal of Mechanical Sciences*, 28, (6):, 381–391.

Malvern, L.E. & Jenkinds, D.A., Tang T., McLure, S. ,1991. Dynamic testing of laterally confined concrete. *Micromechanics of Ffailure of Qquasi Bbrittle mMaterials*, Elsevier Applied Science, 343-352.

Merle, R.& Zhao, H., 2006,. On the errors associated with the use of large diameter SHPB, correction for radially non-uniform distribution of stress and particle velocity in SHPB testing,. *International Journal of Impact Engineering* 32, : 1964–1980.

Novikov, S.A., Divnov, I.I., Ivanov, A.G., 1966. The study of fracture of steel, aluminium and copper under explosive loading. *Fizika Metallov I Metallovedeniye* 21 (4).

Pierron, F.& Forquin, P., 2012,. Ultra-High-Speed Full-Field Deformation Measurements on Concrete Spalling Specimens and Stiffness Identification with the Virtual Fields Method,. *Strain*, Blackwell Publishing Ltd.

Reinhardt, H., W., 1982. Concrete under impact laoading, Tensile Strength and bond, *Heron*, vol 27, n°(3), Delft, The Netherlands.

Rota, L., 1994., An inverse approach of identification of dynamic constitutive equations,. *International sSymposium on Iinverse pProblems*, Ed. . Balkema

Safa, K., 2008., Mise au point d'un essai de compaction dynamique. Application au béton, *P.H.D. 20-10-2008*, Ecole Polytechnique France,

Safa, K. & Gary, G., 2010,. Displacement correction for punching at a dynamically loaded bar end, IE-1835,. *International Journal of Impact Engineering* 37, 2010, :371-384.

Tedesco, J.,W., Ross, C.,A., Kuennen, S.,T., 1993., Experimental and numerical analysis of high strain-rate splitting tensile tests,. *ACI materials Journal*, vol 92 n°(2):,pp. 162-169.

Toutlemonde, F., Boulay C., Gourraud C., 1993., Shock-tube tests of concrete slabs,. Materials and structures, Vol 26, pp: 38-42.

Weibull, W., 1939.. *A Statistical Theory of the Strength of Materials. Report 151*, Roy. Swed. Inst. Eng. Res.

Zhao, H. & Gary, G., 1996,. On the use of SHPB technique to determine the dynamic behaviour of the materials in the range of small strains,. *Int. J. Solid. & Structure*. 33,: 3363-3375.

Zukas J. A. 1982. , *Impact Dynamics*., John Wiley & Sons, 1982.