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Research Article

Dynamic Brazilian Test for Mechanical Characterization of Ceramic Ballistic Protection

Martina Scapin, Lorenzo Peroni, and Massimiliano Avalle

Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca Degli Abruzzi, 24, 10129 Turin, Italy

Correspondence should be addressed to Martina Scapin; martina.scapin@polito.it

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The aim of this work is to identify the tensile strength of alumina (Corbit98), by performing Brazilian tests at different loading rate. In this kind of test, generally used for brittle material in static loading conditions, a cylindrical specimen is diametrically compressed and failure is generated in the middle of the component as a consequence of a positive tensile stress. In this work, this experimental technique was applied also in dynamic loading conditions by using a setup based on the Split Hopkinson Pressure Bar. Due to the properties of the investigated material, among which are high hardness, high compressive strength, and brittle behaviour, some precautions were needed to assure the validity of the tests. Digital Image Correlation techniques were applied for the analysis of high framerate videos.

1. Introduction

An armour system, both for protecting people and vehicles, is a structure made with the objective of stopping the trajectory of an impacting object, such as a projectile. The development of bullets, defined as kinetic energy penetrators, specifically designed to incorporate a hard steel or tungsten carbide penetrator as core, implies the use of multilayer protections, in which, usually, the first layer is made of ceramic materials, since they offer a good compromise between hardness, mechanical resistance in compression, and lightness.

The problem related to ceramic materials is that they are very brittle and can crack or fail because of a tensile wave generated from the reflection of the compressive one at the back free surface of the entire armour system. For these reasons, usually one or more rear layers, made of a ductile material (metallic and/or polymeric composite), are used to block the ceramic debris. The tasks of the ductile plates are also to support the ceramic tiles during the impact, delaying the crack initiation in the ceramic layer and absorbing the remaining kinetic energy of the projectile.

In general, during the impact between projectile and ceramic tile, the high strength of the two involved materials directly compete. Due to the high velocity at which the impact occurs (greater than 800 m/s), the strain state of the ceramic tile can be well approximated with a uniaxial strain (like in a flyer plate test) with a triaxial stress state and a consistent hydrostatic component. This implies that the material property of importance in the design of armour devices is the Hugoniot Elastic Limit (σ_{HEL}), which, for a brittle material, represents the stress value at which the material stops to be able to resist penetration. This means that a good candidate material for armour devices must have a very high σ_{HEL} combined with a high value of hardness. Another important aspect is related to the fact that the impact produces the sudden generation of shockwaves in the materials that propagate and are reflected at the interfaces. In the ceramic tiles, both planar and cylindrical waves are generated. The former propagate and when they reach the interfaces, they are reflected into tensile waves which can be responsible for the material failure by spalling. The latter propagate radially from the impacted zone and this produces a considerable tensile state in the hit part which is behind the shock front. This implies that, for a complete material characterization, the investigation of the tensile strength of ceramic materials is fundamental also, especially in the dynamic regime. This represents the basis of the present work, which is a part of a big research project, in which the final goals are the evaluation and the prediction of the response of a multilayer ballistic protection.

As previously described, the global response is strongly affected by the behaviour of the ceramic layer, which, in the present case, is made of alumina with a purity of 98% (Corbit98). Alumina is one of the most widely used materials in the family of engineering ceramic with an excellent combination of properties and an attractive price, which allows alumina to find applications in a very wide range of fields, including aerospace, civil, nuclear, and military applications [1–4]. A summary of its properties includes very high compressive strength (>3 GPa), high hardness (>70 HRC), low density (3.6–3.8 g/cm^3), high speed of sound (>7 km/s), high operating temperature (up to 1500°C), high corrosion and wear resistances, good electrical insulation, and moderate thermal conductivity.

This work showed the results of the experimental investigation of the strength at failure under quasi-static and dynamic tensile loading conditions for Corbit98. The material characterization was obtained by performing Brazilian (or splitting) tests on cylindrical specimens. The high loading rate conditions were reached by using a Split Hopkinson Pressure Bar setup. High speed videos of the tests were acquired and used to validate the experiments by checking the crack propagation. The experimental results were analysed in order to investigate the sensitivity to loading rate and determine the maximum tensile strength of the material.

2. Bibliographic Review

The mechanical characterization of brittle materials, especially ceramic ones, under dynamic tensile loading condition represents an up-to-date research field especially due to the continuously increasing interest in the use of this class of materials for various applications. The experimental phase is a challenging task, even in quasi-static loading conditions, because the brittleness and hardness of these materials complicate the machining of specimens (often it is not possible to obtain dog-bone specimens for standard tensile tests) and the design of load transfer mechanisms (bending and misalignment can easily produce the early failure of the specimens). As expected, these difficulties become more important in the dynamic regime.

For all these reasons, during the years, other indirect methods were applied, such as bending tests, from which the tensile behaviour was derived. With the aim to investigate the response in tension, in [5] an alternative testing method, the Brazilian (or splitting) test, was developed and applied to concrete for quasi-static tests and now there is the ASTM C 496-71 standard for carrying out this type of experiments [6]. The procedure implies the diametrical compression of a disk of material, which produces a tensile stress state in the specimen which is maximum and constant along the diameter coincident with the loading direction: hence the failure occurs along this direction. The scheme of the stress distribution in the specimen is represented in Figure 1 [7]. The assumptions on which the test is based are that the material is homogeneous and isotropic and it behaves elastically and

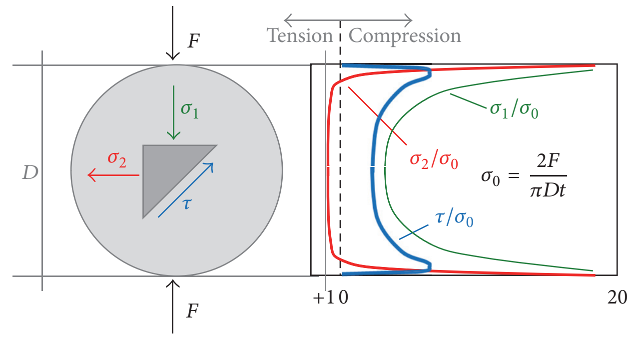


FIGURE 1: Qualitative stress state distribution developed in the specimen during a Brazilian test.

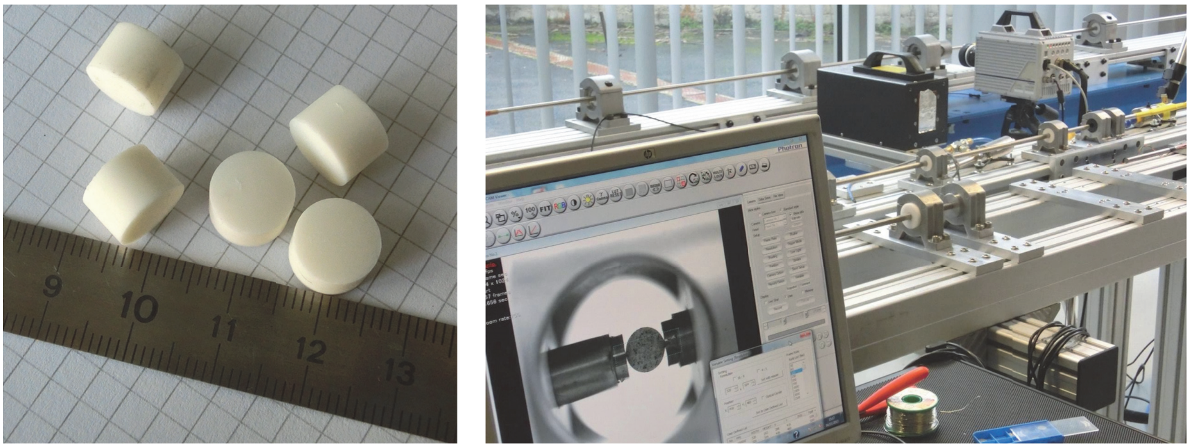
presents shear and compression strengths greater than the tensile strength.

With reference to the scheme reported in Figure 1, the principal stress σ_2 is the unique positive stress component and it is quite constant over the diameter. Under the above-mentioned assumptions, the tensile stress can be derived from the following equation:

$$\sigma_0 = \frac{2F}{\pi Dt}. \tag{1}$$

F is the value of the applied load and D and t are, respectively, the diameter and the thickness of the specimen. By increasing the load, the tensile stress grows until a crack is generated in the middle of the sample, which is divided into two parts: the tensile strength can be determined by the (1) as a function of the applied load when the crack is initiated. An important positive characteristic in favour of this technique rather than a bending test is that the tensile strength is directly derived, it is not limited to the surface, and the fracture starts internally. The latter aspect represents the necessary condition for the proof of the validity of the test.

Over the years, this experimental technique was improved and extended to the investigation of the dynamic behaviour by applying the load at high strain-rate via a Split Hopkinson Pressure Bar setup. In the scientific literature it is possible to find a lot of works; see, for example, [8–21], in which this technique was applied to several brittle materials, among which are concrete, rocks, ceramics, glass, syntactic foams, frangible bullets, metal matrix composites, and compacted powders based materials. In most of these works, a critical analysis of the results was performed to study the real stress distribution inside the specimen which, in general, is influenced by several factors, such as the area and the way in which the load is applied, the friction and the interaction with the plates, the specimen dimensions, the presence of plastic deformation, and, obviously, the material properties. Moreover, in dynamic regime, other problems arise from wave propagation and a possible nonequilibrium condition: to partially solve this problem, the pulse shaping technique was widely adopted, since a strong influence was found on the shape of the incident wave. To prevent stress concentration at the loading areas, curved anvils or flattened specimens were adopted. In many cases, high speed videos



(a) (b)

Figure 2: Specimens used for Brazilian test (a); detail of the Split Hopkinson Pressure Bar for high loading rate tests (b).

were acquired and used as a tool to prove the validity of the test or to better analyse the experimental results by applying Digital Image Correlation (DIC) techniques. In a lot of works, Finite Element simulations were used to check and design the experiment itself or to calibrate and tune the failure models. In some cases, by introducing precrack or notch, the Brazilian test as well as its modified versions was applied to find stress intensity factor and fracture toughness [22]. This approach is usually followed when it is supposed to be some defects with a relevant dimension (from an engineering point of view) in the material, which is not the cases of this samples.

For what concerns the state of the art on the mechanical characterization of alumina, a lot of works can be found on compressive and shock experiments [23–26], while only few works showed the results of tensile characterization [22, 27, 28], applying spalling and Brazilian tests. The sensitivity of the mechanical response of this material to the grade of purity jointed with the extremely low amount of available data on tensile strength at fracture of alumina at 98% highlights the necessity to get a reliable and exhaustive material characterization, since, as mentioned in the Introduction and discussed also in [25], the behaviour of a specific armour under impact is strictly dependent on the tensile behaviour of the ceramic material along with the fragmentation process.

3. Experimental Procedure

In this work, the cylindrical specimens are made in alumina with a purity of 98% (Corbit98) with a diameter of 9.60 mm and a thickness of 7.00 mm (Figure 2). The specimens were obtained via powder sintering process and each specimen was inspected and no damage or cracks were found; the quality of the surface roughness and the specimen porosity are those required for the armour tile.

The Brazilian test was performed both in quasi-static and dynamic loading conditions: the low loading rate tests were performed on a standard electromechanical testing machine (Zwick Z-100), while a direct Split Hopkinson Bar setup

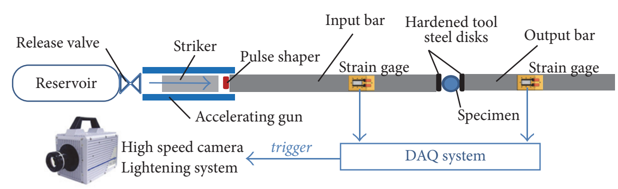


Figure 3: Scheme of the Split Hopkinson Pressure Bar for high loading rate tests.

was used to reach a higher loading rate. For what concerns the static tests, no particular precautions were adopted: the specimens were diametrically compressed by interposing small disks of hardened tool steel to avoid indentation of machine plates. To perform high loading rate tests small modifications were made on the standard setup used for compression tests [29]. The scheme of the setup is reported in Figure 3.

The main modification regards the tuning of an ad hoc pulse shaping technique, which, as widely discussed in the scientific literature, is necessary to avoid that the fracture of the specimen occurs in a nonequilibrium phase. When the striker impacts against the input bar, at its interface, an almost rectangular compressive wave is generated which is characterized by a rising time of about few microseconds. This implies high acceleration and high frequency oscillations which affect the force signal in the initial phase before reaching the equilibrium condition. When the material under investigation reaches high level of deformation, this portion is negligible in comparison to the total test duration. Otherwise, in case of a brittle material, for which the test terminates at the end of the elastic phase, in order to assure the fracture occurring at the equilibrium, it is necessary to smooth the rise of the wave, diluting it in time. This condition is reached by interposing a disk made of soft material (pulse shaper) between the striker and the input bar. In this work a disk of copper (with a thickness between 1 and 2 mm) was used, able to allow the generation of a triangular wave. In Figure 4, the

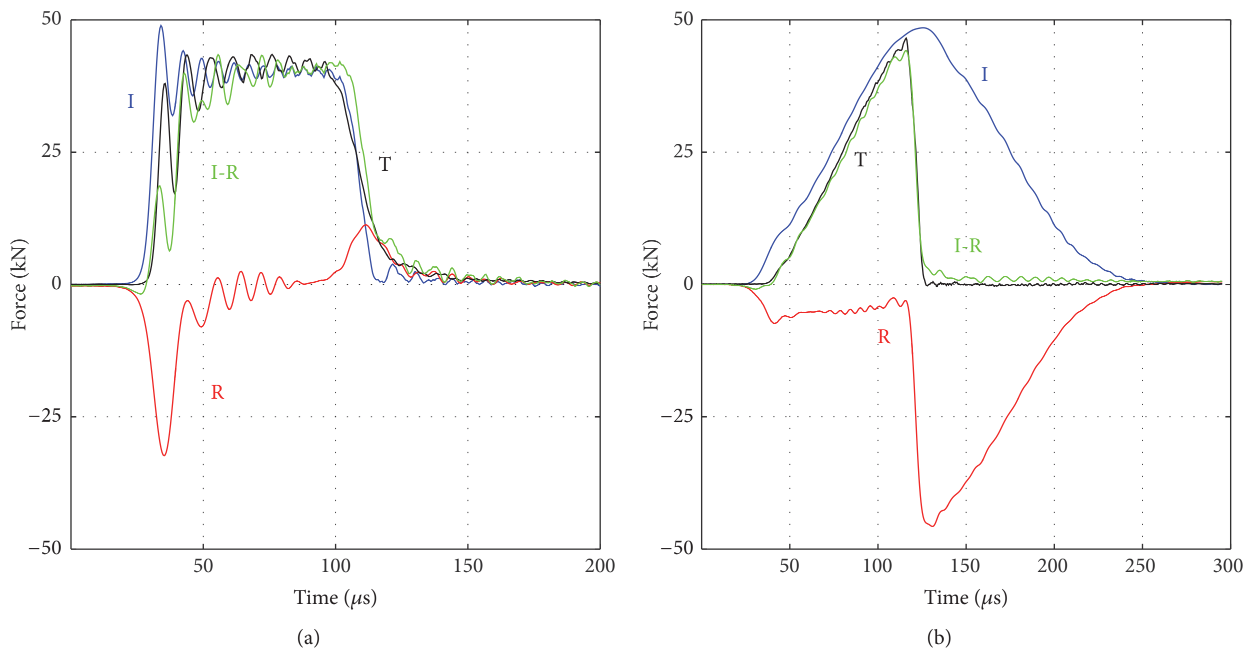


Figure 4: Check of the equilibrium condition on the specimen: waves diagram without (a) and with (b) the pulse shaper.

strain-gage signals, acquired during two tests, one with and the other without the pulse shaper, are reported. The waves are labelled as follows: incident one as I, transmitted one as T, reflected one as R, and, finally, the difference between incident and reflected waves on the input bar as I-R. From the comparison between the two diagrams it is possible to appreciate the improvement obtained with the pulse shaper: in this case, by comparing the forces acting on the two sides of the specimen (T and I-R waves), it is possible to notice that the equilibrium condition is reached at the beginning of the test, in contrast with what happens without the interposition of the pulse shaper.

The problem related to the use of the pulse shaper is the consequent uncertainty in the value of the loading rate which is reduced and not constant, in comparison with the quasi-static case, in which it is imposed and constant over the entire test. This fact implies that for each dynamic test it is necessary to elaborate the strain-gage signals to extract the correct loading rate. The second modification with respect to the setup reported in [29] is related to the diameter of the bars (made of 17-4PH). Due to the high strength of the material, the requirement is to generate a compressive wave greater than 40 kN which is the limit for bars with 10 mm of diameter: for this test campaign bars with 12 mm of diameter were adopted. Also for Hopkinson tests, low thickness disks made of hardened tool steel were interposed between bars and specimen to avoid bars indentation (bars have a hardness of 40 HRC): the disks have 10 mm of diameter and 3 mm of thickness and do not introduce any perturbations or impedance mismatching for the wave propagation. To avoid friction effects, disk with a very fine roughness of the surface was adopted and a thin layer of grease was interposed between disks and specimen.

In order to get high framerate video of the fracture to be used for the test validation, the high speed camera Photron SA5 was used in the dynamic case. The problem related to the video acquisition is the synchronization with the test (and, in particular, with the fracture) and the lightening system (flash). In case of dynamic test, the strain-gage signal of the input bar is used to generate a trigger signal needed for starting camera and flash.

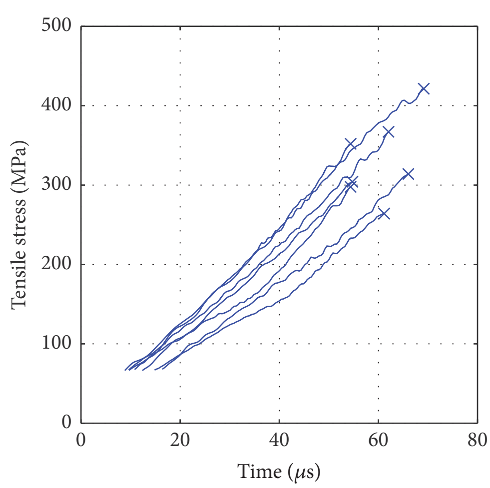
On the contrary, for quasi-static tests it was not possible to record the fracture event. A quasi-static test has a total duration of some seconds, but the crack propagation occurs at a velocity equal to a fraction of the sound speed in the material. This requires the use of a high speed camera to record the phenomenon at high framerate and, in turn, this implies the use of a proper lightning system. In this work, a flash system is used, which has duration of constant light limited in time (about 1 ms) which is not enough to follow the entire event and it should require a trigger signal for starting, which was not available.

4. Experimental Results and Data Analysis

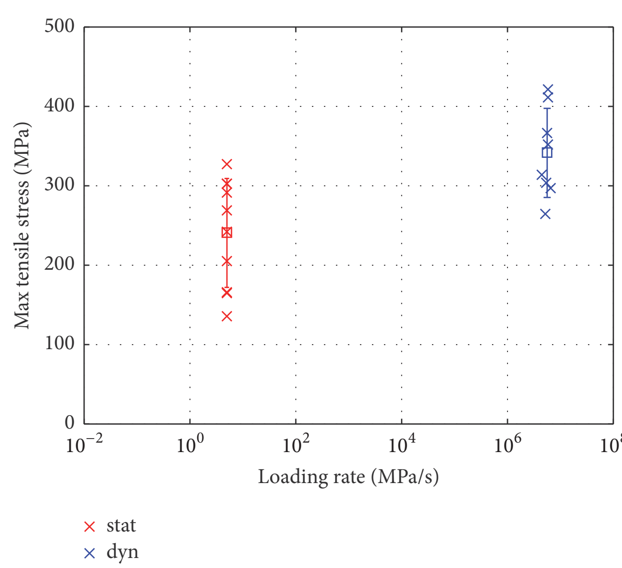
During the testing campaign, a total of 18 tests were performed: 10 in quasi-static loading condition and 8 at high loading rate. In Table 1, the results of all the tests are summarized in terms of maximum tensile strength calculated on (1) and loading rate (mean value in case of dynamic tests). As expected, the scatter of the experimental results is quite high: the strength varies between a minimum of 135 MPa and a maximum of 327 MPa in the quasi-static case and between 265 and 422 MPa at high loading rate. Some possible explanations of the high data scatter can be related

Table 1: Experimental results for Brazilian tests on alumina (Corbit98).

Type of test	Specimen ID	$\sigma_{0\max}$ (MPa)	$\sigma_{0\max,\mathrm{mean}}$ (MPa) ± std (MPa)	Loading rate (MPa/s)
Static	1	204.9	240.7 ± 68.6	5
	2	241.8		5
	3	291.1		5
	4	327.4		5
	5	303.0		5
	16	166.1		5
	17	269.2		5
	18	302.9		5
	20	135.4		5
	21	164.7		5
Dynamic	9	411.1	341.5 ± 56.1	$5.9e+6$
	10	366.8		$5.7e+6$
	11	303.9		$5.4e+6$
	12	351.8		$5.9e+6$
	13	421.7		$5.9e+6$
	14	297.6		$6.6e+6$
	15	264.6		$5.1e+6$
	17	314.0		$4.4e+6$



(a)



(b)

Figure 5: Experimental results in terms of force versus time curves for high loading rate tests (a) and maximum tensile stress at failure versus loading rate (b).

to the brittle behaviour of the materials as well as to the manufacturing process (sintering). In quasi-static conditions, the mean value of the maximum tensile strength is 241 MPa with a standard deviation of ±69 MPa; at high loading rate 342 ± 56 MPa was found (these values are summarized in Table 1). In Figure 5, the stress at failure as a function of loading rate is also reported. By looking at the diagram, it is possible to notice that the material seems to be slightly loading rate sensitive: the material strength increased by increasing the loading rate. The trend and the data scatter are comparable to those reported in [28, 30] for similar materials, even if the values of strength, both in quasi-static and high loading rates, are higher.

By looking at the loading rate variation in dynamic tests, it is possible to conclude that the presence of the pulse shaper has a secondary influence on the effective loading rate; hence, the loading rate can be considered equal in all the performed tests.

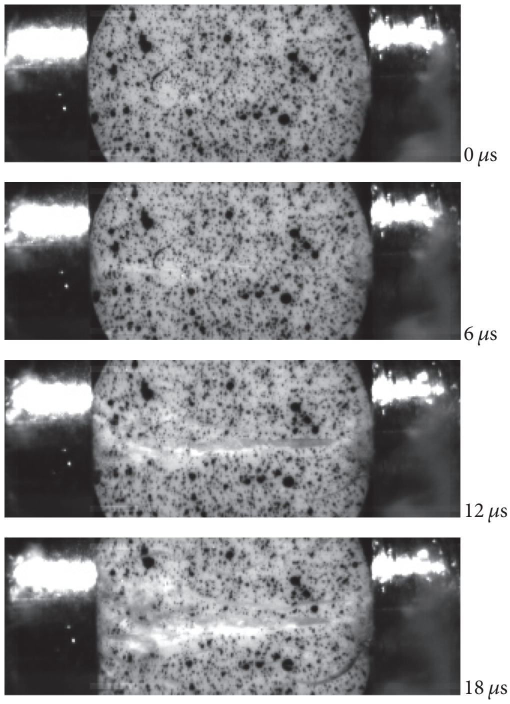


Figure 6: Sequence of the high speed video acquired during dynamic test at 175000 fps at a resolution of 320 × 104 pixels: the crack is visible starting from the second image (specimen ID 13).

In Figure 6, some frames recorded during high loading rate test are reported: the entire duration of the test is about 100 μs and it was recorded with a framerate of 175000 fps.

A more in depth analysis of the experimental results in dynamic regime was performed by analysing the dynamic test for which a good quality high speed video was recorded. The data extracted from the video were compared with the force measurement and the results are summarized in Figure 7. For each test, a diagram showing the check of the equilibrium is reported: the force measured by input and output bars was synchronized and managed in accordance with (1); hence the check is performed in terms of σ_0. As it is possible to notice, for all the reported tests, the equilibrium is reached starting from the beginning of the test. In each diagram, two vertical dashed lines identify the time of two subsequent frames after the crack formation. Due to the high sound speed and the small dimension of the specimen, the time interval between two frames is greater than the time needed for the crack to propagate through the entire specimen diameter: this means that it is not possible to appreciate the crack formation. For each video, a Digital Image Correlation (DIC) analysis was performed with the aim to investigate the displacement in the opening direction (vertical). For each test, two images are reported. On the first one (corresponding to the first vertical line in the diagram), the spatial distribution of the vertical displacement is reported: the crack is clearly visible as well as the displacements in opposite directions of the two parts in which the specimen is broken. The last test (specimen ID 17) is a little bit different since it was characterized by a significant specimen failure at the output bar interface (right side). For each test, the second image is the next frame, in which the crack is clearly visible (corresponding to the second vertical line in the diagram). By tracking some points on the speckled specimen surface (i.e., virtual strain gages), it was also possible to measure the crack opening displacement (COD) and from this to estimate the separation velocity of the specimen stumps. The time history of the COD is reported in the same diagram of the force equilibrium: it remains small in the first part of the test and then it starts to significantly increase in correspondence to the maximum of the load. An example of the measurement of the opening displacements is reported in Figure 8.

The estimated velocity is reported as a function of σ_0 in the diagram of Figure 8. The projection velocity and the stress at failure are linearly correlated, since the moving velocity of the stumps after failure is related to the internal energy stored inside the specimen and released at the crack generation. By comparing these results with those reported in [22], it is possible to notice that the velocity is considerably higher and again this is in accordance with a higher material strength at failure. Due to the lower velocity, in [22], it was possible to obtain a high number of frames after fracture to be used to estimate the COD; otherwise in the present case, a limited number of frames could be used even if the videos were acquired with a higher framerate.

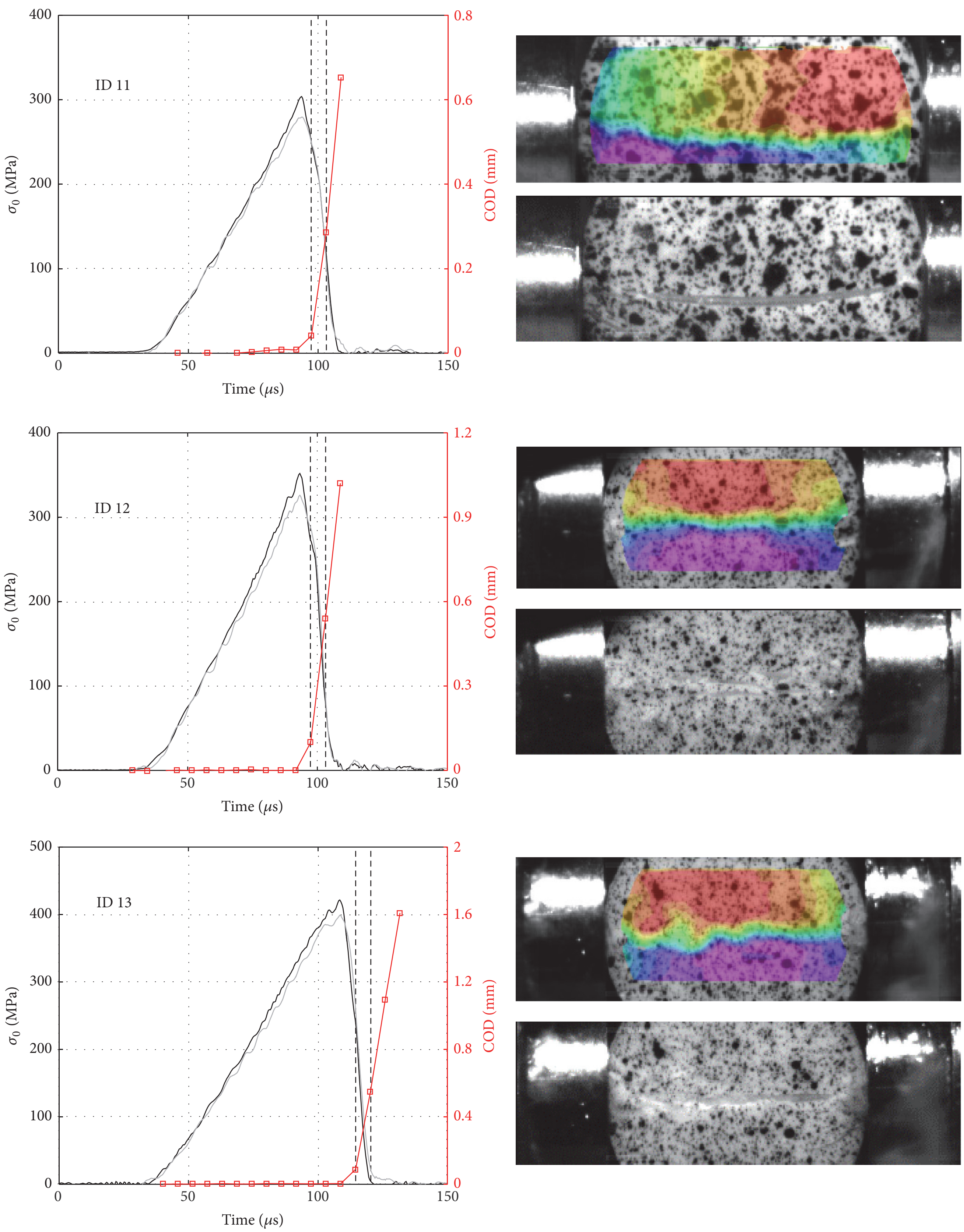
5. Conclusions

In this work the tensile strength at failure of Corbit98, both in quasi-static and dynamic loading conditions, was investigated. The attention to the tensile properties of this material comes from the use as layer of armour protection. The lack in the scientific literature of available data for this material reveals the need of an ad hoc testing campaign.

The material characterization was performed by using the Brazilian test, which consists of a diametrical compression of a cylindrical specimen and allows extracting the tensile strength at fracture. The low loading rate tests were conducted on a standard electromechanical testing machine, while a Split Hopkinson Pressure Bar setup was used to reach high loading rate. In addition, a high speed camera was used to get the videos of the fracture events.

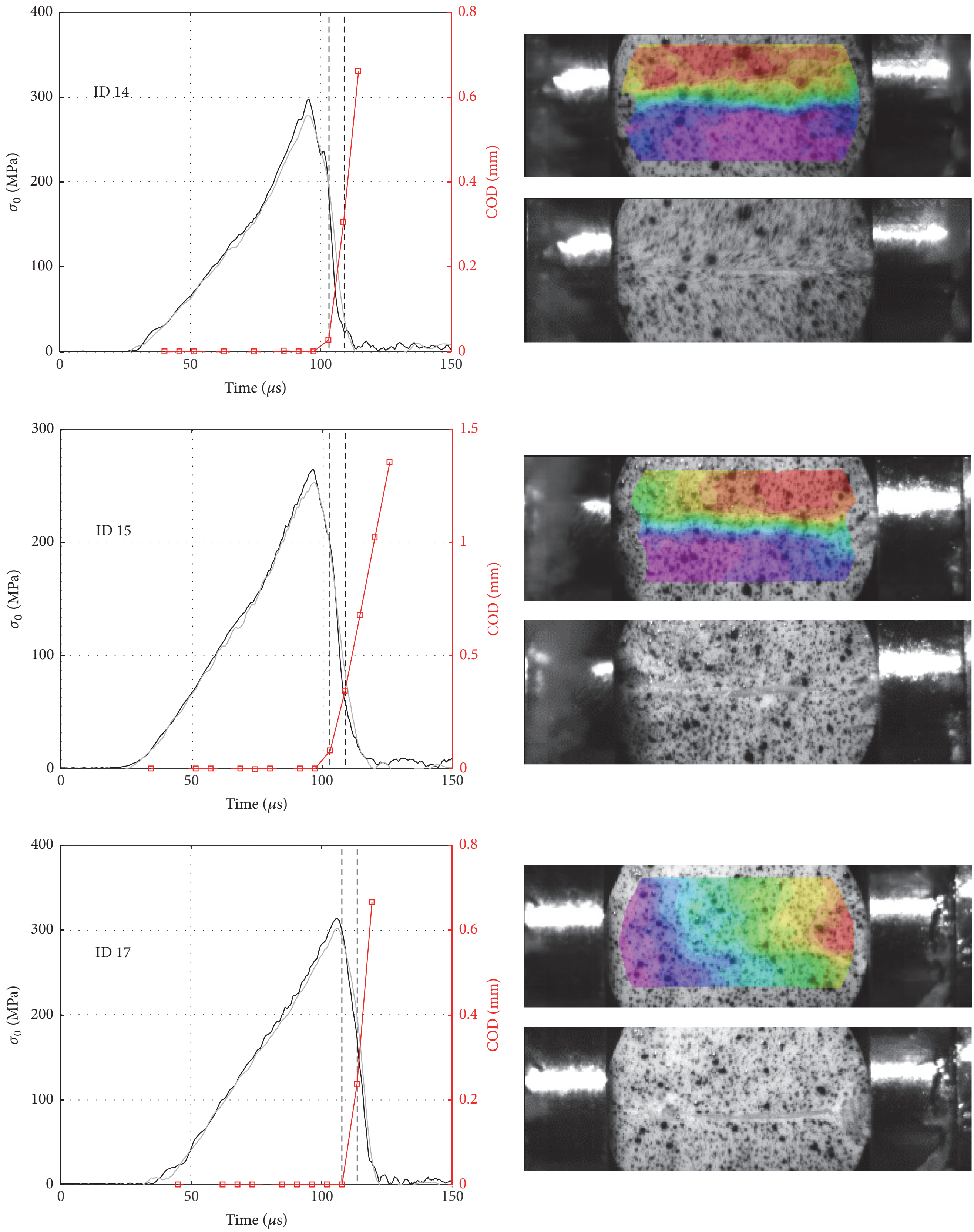
Due to the properties of the investigated material, among which are high hardness, high compressive strength, and brittle behaviour, some critical points had to be addressed to obtain valid tests. In particular, in both quasi-static and dynamic cases, hardened tool steel disks were interposed at the interface between the testing equipment and the specimen. Moreover, in high loading rate tests, the oscillation and inertia phenomena had to be limited by using pulse shaping technique to assure equilibrium condition on the specimen. Finally, due to the high material strength a new ad hoc Hopkinson setup was built to be able to generate the load necessary to fracture the specimens.

A classical approach was used to extract the maximum tensile stress at failure starting from the force versus time curve. As expected for this material, a quite big scatter was found in both quasi-static and dynamic regime. DIC



(a)

Figure 7: Continued.



(b)

Figure 7: Analysis of the results obtained from dynamic Brazilian test. In the diagrams: equilibrium check by the comparison between input (gray curve) and output (black curve) forces; COD (red curve with markers) calculated by the vertical displacements measured by virtual strain gages placed along the diameter above and under the crack. The images represent two subsequent frames recorded after fracture: DIC analysis for the evaluation of the vertical displacement.

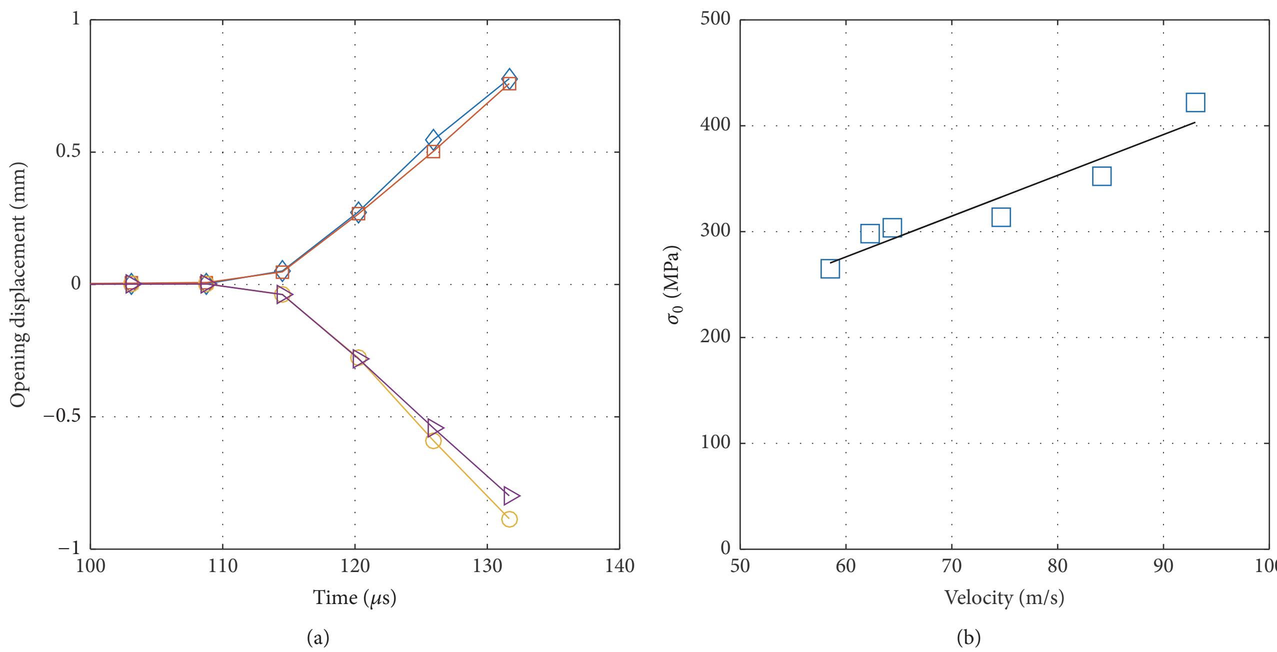


FIGURE 8: Opening displacement measurement and evaluation of the correlation between σ_0 and the separation velocity.

analysis was applied to high speed videos to obtain the time history of the displacement distribution inside the specimen after fracture. This allows estimating the stumps separation velocity which is correlated to the elastic energy stored and consequently to the stress at failure. By investigating the loading rate influence on the maximum tensile strength, it was found that the material is slightly sensitive on it.

Additional Points

Highlights are tensile strength characterization of brittle materials, execution of quasi-static and dynamic Brazilian test on Corbit98, and high loading rate tests on Split Hopkinson Pressure Bar setup.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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