A NOVEL METHOD FOR MEASURING THE DYNAMIC FRACTURE-INITIATION TOUGHNESS UNDER IMPULSIVE LOADINGS

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The design and development of a new method for performing fracture toughness tests under impulsive loadings using explosives is presented. The experimental set-up was complemented with pressure transducers and strain gauges in order to measure, respectively, the blast wave that reached the specimen and the loading history. Fracture toughness tests on a 7017-T73 aluminium alloy were carried out by using this device under impulsive loadings. Previous studies reported that such aluminium alloy had very little strain rate sensitivity, which made it an ideal candidate for comparison at different loading rates. The fracture-initiation toughness values of the 7017-T73 aluminium alloy obtained at impulsive loadings did not exhibit a significant variation from the cases studied at lower loading rates. Therefore, the method and device developed for measuring the dynamic fracture-initiation toughness under impulsive loadings was considered suitable for such a purpose.

INTRODUCTION

Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture. Such a characteristic is one of the most important properties for describing the failure criteria of materials and may be a function of loading velocity and temperature. Therefore, in the case of materials that may be subjected to dynamic loads, it is crucial to be aware of how their fracture behaviour varies with the loading rate.

In static conditions, the ASTM E399 standard [1] describes the test method for plane-strain fracture toughness of metallic materials. This test method, in which fracture mode I is assumed, involves testing of notched specimens that have been fatigue pre-cracked, loading them either in tension or three-point bending configurations. Load versus displacement across the notch at the specimen edge is recorded. The stress-intensity factor, K_I, predicts the stress state near the tip of the crack caused by the remote load. The fracture toughness value, K_{IC}, is the critical value of the stress intensity factor.

Under dynamic conditions, as the fracture behaviour of the materials may be a function of loading velocity, a different parameter should be defined. Such a parameter is the dynamic fracture-initiation toughness, K_{Id}. The crack starts to grow when the stress-intensity factor, $K_I(t)$, reaches a critical value, the K_{Id}. Therefore, the dynamic fracture-initiation toughness can be calculated as, $K_{Id} = K_I(t_f)$, where t_f is the moment when the crack starts to grow.

Obtaining fracture toughness under dynamic conditions is somewhat complex because the specimen might not be under stress equilibrium. At present, there are no standards or guidelines to calculate dynamic fracture toughness, though several methods are based on combining the stress-intensity factor history obtained from numerical simulations with the failure moment being determined from the experiments, e.g., as [2] and [3]. Optical techniques and the coherent gradient sensing (CGS) method have also been used in dynamic fracture studies, e.g., as [4]. Furthermore, several Hopkinson bar configurations and specimen geometries can be found, such as three-point bending configuration, e.g., as [5] and [6], semi-circular bend specimens, e.g., as [7], and Charpy impact specimens, e.g., as [8] and [9].

On the research presented here, the main objective is to develop a new experimental device to perform fracture toughness tests at very high loading-rate using explosives.

An explosion may be defined as an event that occurs due to a sudden release of energy within a limited space. However, an explosion in which the chemical energy of a certain explosive compound is liberated should be called detonation. In such a detonation, a blast wave is formed by a difference in the air pressure on both sides of the shock front and moves away at high speed from the detonation point. Unconfined explosions are those that take place in the open air. Particularly, free air explosions are those where the shock wave reaches the structure with no intermediate disturbances.

As in previous studies, e.g., as [10], [11] and [12], in this research the dynamic fracture-initiation toughness values under impulsive loadings are compared with the corresponding value obtained at lower loading-rates.

MATERIAL DESCRIPTION

The material tested was a 7017-T73 aluminium alloy. Initially, this was selected because its mechanical behaviour had been found to be nearly independent from the strain rate [13]. Fracture toughness tests of such a material were previously performed by Pérez-Martín et al. [14] at different loading-rates. In such a study, the fracture-initiation toughness of the material remained constant regardless of the velocity at which the load was applied. Therefore, the obtained results in this research could be compared with the results at lower loading-rates.

One of the highest strength aluminium alloys and that mainly used in armoured vehicles is 7017-T73 aluminium alloy. It contains zinc as the primary alloying element, magnesium and chromium. Magnesium produces a marked improvement in precipitation hardening characteristics and chromium provides an increase of the stress corrosion cracking resistance. The alloy was solution heat-treated with artificial aging. Such treatment leaves the material beyond the point of maximum strength and achieves the best stress corrosion resistance. The chemical composition in weight percentage and mechanical properties are summarised in Table I and Table II respectively.

There can be found several possible specimen configurations for obtaining the fracture toughness of metallic materials. In this research, the standard bend geometry was selected. The standard bend specimen is a single edge-notched and fatigue-cracked beam loaded in a three-point bending configuration. The dimensions of the specimens were 126 x 15 x 30 mm, with a notch of 14 mm and a pre-crack of 2 mm (see Figure 1(a)).

EXPERIMENTAL SET-UP

A new device was designed and developed to perform fracture toughness tests under explosive loadings. It allowed the simultaneous testing of up to two three-point bending samples, thus making it possible to control de experimental scatter of the tests.

TABLE I. CHEMICAL COMPOSITION OF 7017-T73 ALUMINIUM ALLOY (WEIGHT %).

Zn	Mg	Fe	Si	Cu	Mn	Cr	Zr
5.1	2.4	0.3	0.16	0.12	0.22	0.16	0.12

TABLE II. MECHANICAL PROPERTIES OF 7017-T73 ALUMINIUM ALLOY.

E (GPa)	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	ε_f (%)
71	450	499	12

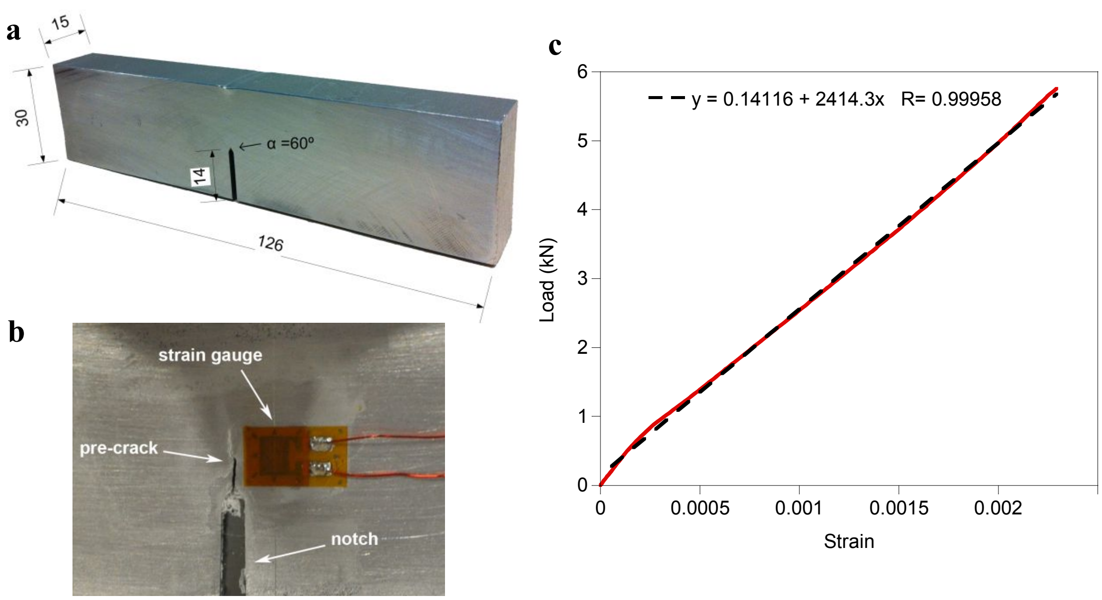


Figure 1. (a) Dimensions of the standard bend specimen. (b) Detail of the bonded strain gauge close to the tip of the fatigue crack. (c) Linear relationship between the applied load and measured strain.

Set-up description

A steel frame, designed by Morales-Alonso [15], [16] and [17], for testing concrete samples under blast loading, was used to bear the new device. It consisted of four vertical steel columns joined horizontally by steel beams, with it being square in plan view (see Figure 2(a)). These horizontal beams acted as support for the devices. The steel frame was a symmetric structure in which the explosive was hung at its geometrical centre. It was considered a braced structure when subjected to the blast wave. The new device and the explosive were placed on a horizontal plane above the ground, with its height being greater than the distance from the explosive to the device (see Figure 2(c)). By doing this, the blast shock wave reached the device directly. In addition, the shock wave reflections reached the device after it was hit by the incident wave. This enabled the explosion to be as similar as possible to a free air explosion. Another important point in the success of the experiments was that the blast shock wave should strike every point of the exposed surface of the device at the same time. In other words, the shock wave should be as planar in shape as possible. This requirement did not match with the spherical shaped shock waves generated in an open air explosion. As the device was small enough and was far enough from the explosive, the curvature of the striking shock could be neglected and the shock wave could be assumed to be planar. Dimensions of the steel frame were set to 3.00 m between columns, stand-off from explosive to the device to 1.50 m, and height of the centre of the device to 1.60 m.

A new device was designed and developed to perform a three-point test under explosive loadings. It was mounted on the steel frame as can be seen in Figure 2(b). The device allowed testing of two specimens simultaneously (see Figure 3(a)). It consisted of a 146 x 146 x 90 mm steel box with its cover, exposed directly to the explosive, was made of a composite laminate. The two specimens were positioned on two cylindrical roller bearings, as it can be seen in Figure 3(c). A steel cylinder attached to the composite laminate was the load applier. When the shock wave reached the laminate it was moved into the box and loaded the specimens. The laminate was composed of several carbon and glass-fibre plies. Due to the low weight of such a component, close to 0.4 kg, higher load application velocities could be achieved. Two coil springs were installed in order to guarantee that the load applier was initially in contact with the specimen (see Figure 3(b)). Four devices were manufactured with the same configuration and dimensions.

The explosive used for the detonations was the commercial compound Goma 2 ECO, with a density of 1.48 g/cm^3 and a combustion heat of 89% of the energy release of 1 kg of TNT. The explosive was presented in bars. The bars were 200 mm in length and 8 mm in diameter and were tied together forming a cylindrical bunch. In order to preserve the blast wave symmetry as far as possible, the explosive pack was vertically hung (see Figure 3(d)).

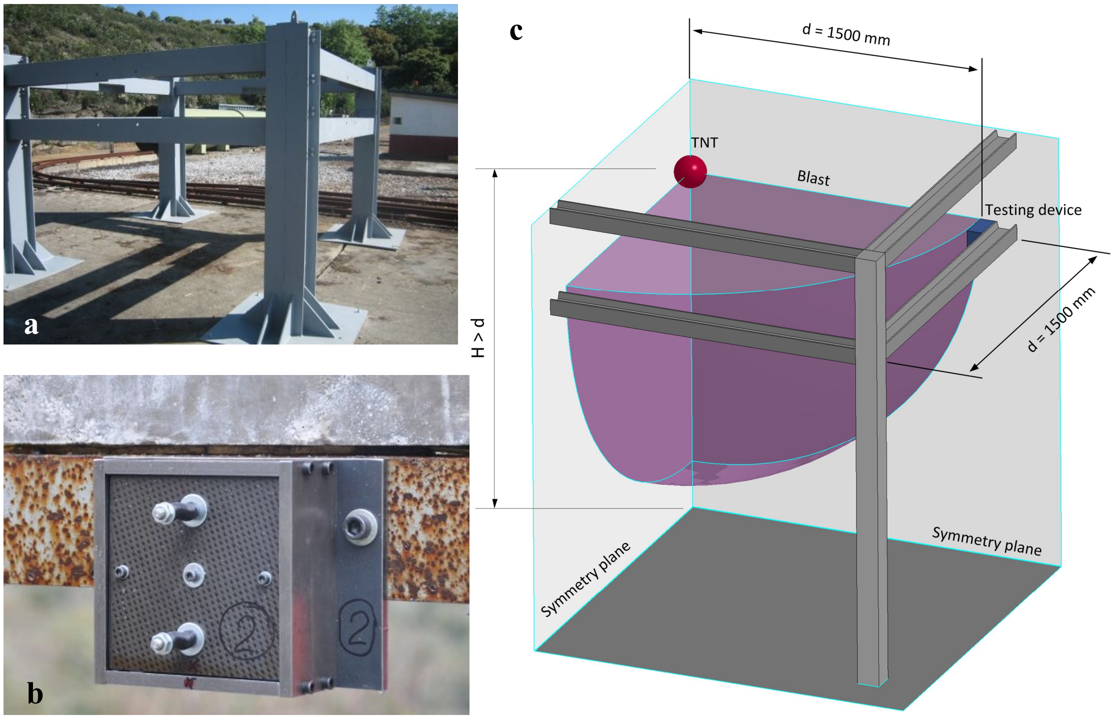


Figure 2. (a) The steel frame with a bunker located close to it. (b) The device mounted on the steel frame. (c) A schematic view of the experimental set-up.

Instrumentation

A strain gauge was bonded close to the tip of the fatigue crack of each sample (see Figure 1(b)). The measured strain signal obtained was associated with the load applied to each specimen. This was considered as an indirect method of load measurement that was particularly important in these tests, given that they lacked a load cell. In order to obtain the relationship between the applied load and measured strain, the pre-cracked sample had been subjected previously to a loading and unloading cycle without any crack propagation. Such a relation was found to be linear and was different for every sample (see Figure 1(c)). A strain gauge from Micro-Measurements, model CEA-13-062UW-350, was attached to each sample. Its signal was treated with a 2210 signal conditioning amplifier system from Micro-Measurements, and recorded by a Tektronix TDS714L oscilloscope.

In order to measure the reflected pressure history of each detonation, two piezoelectric pressure sensors were located on the same vertical plane as the device and at the same distance from the explosive. Two sensors from PCB Piezotronics, model 102B, were used. Their signals were conditioned on an ICP signal conditioner from PCB Piezotronics, model 482C05, and recorded by a Tektronix DPO2024 oscilloscope. The data acquisition systems were set on a bunker located at a stand-off distance of 20 m from the detonation point.

The trigger signal for the strain gauge and pressure sensors was made by short-circuiting a DC electrical signal. A 4.5 V battery was connected to a cable wrapped around the explosive. When the explosion opened the circuit, the voltage decayed and triggered the equipment.

Figure 3. (a) Two specimens mounted on the cylindrical supports in the steel box. (b) The steel box with the composite laminate cover. (c) The interior layout of the box: two cylindrical supports, the load applier attached to the composite laminate and the specimen with an attached strain gauge. (d) Detail of the device mounted on the steel frame and the hung explosive.

EXPERIMENTS

Experimental procedure

Open air detonation tests were carried out on 11 April 2013 at the Fundación Santa Bárbara test fields in La Ribera de Folgoso, in León, in Spain. Unfortunately, as the tests were performed in an open field, the climatic conditions were rainy with low atmospheric pressures, high humidity levels and low temperatures (7 ºC).

Four detonation tests were carried out by using the four new devices, which meant that eight specimens were tested. It should be taken into account that the maximum amount of explosive was limited to 5 kg of equivalent TNT due to restrictions of noise pollution legislation. In the first and the second detonations, 4.572 kg of equivalent TNT (4.783 kg of Goma 2 ECO) were used while in the third and in the fourth, 3.325 kg of equivalent TNT (3.478 kg of Goma 2 ECO) were employed. Altogether eight fracture toughness tests were conducted at a load application velocity of 20 m/s in the first and second detonations, and reaching 13 m/s in the last two detonations. Two of the reflected pressure histories can be seen in Figure 4(a).

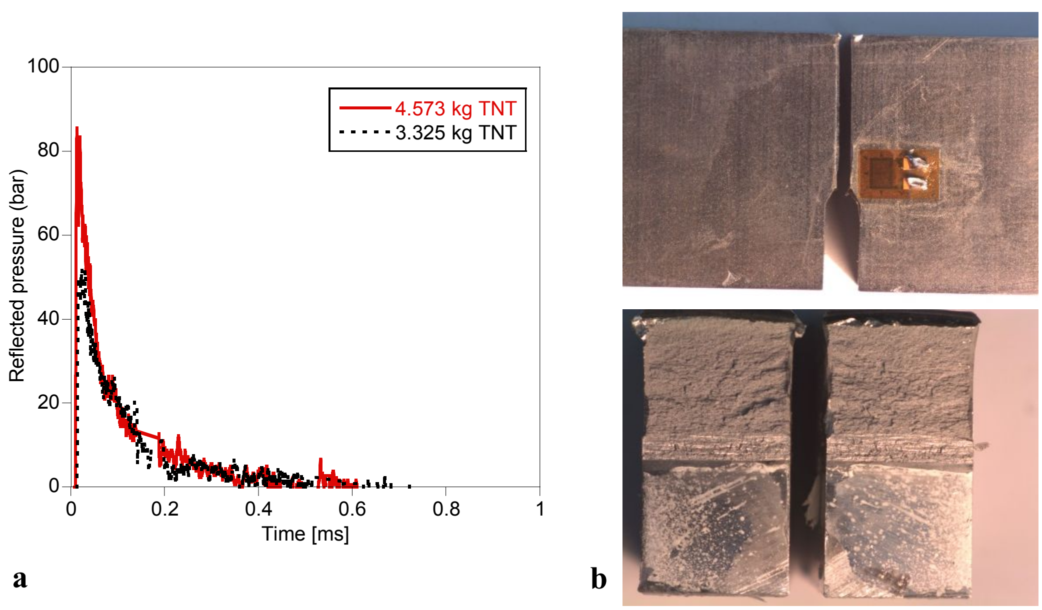
After each explosion, the device and the broken samples were recovered (see Figure 4 (b)). It should be noted that all the devices were recovered completely undamaged and even the composite laminates were unspoilt.

Results

Once all the tests had been performed, the crack length for each specimen was measured and the dynamic fracture-initiation toughness for each specimen determined. The applied load was obtained by using the strain gauge measurement with the linear relationship calibrated specifically for each specimen. The fracture-initiation toughness values for the 7017-T73 aluminium alloy obtained in the four detonations are shown in Figure 5(a).

In order to validate the new experimental set-up as a way to measure the dynamic fracture-initiation toughness under impulsive loadings, the obtained results were compared with those found in the previous research [14] for the same aluminium alloy at lower loading-rates. In such research, fracture toughness tests were carried out at load application velocities of $3 \cdot 10^{-6}$ m/s, 4 m/s and 10 m/s, respectively employing a servo-hydraulic universal testing machine, a free-drop tower and a modified Split Hopkinson Pressure Bar. A comparison of the mean values and their standard deviations are shown in Figure 5(b).

The four experimental devices provided a mean value of 33 $MPam^{1/2}$, with even the standards deviations being similar. In the case of the explosive tests carried out, the scatter was easy to explain because of the nature of the experiments. The tests were subjected to a non-regulated and non-laboratory environment. The detonation depended on the atmospheric conditions and landscape configuration, proof of which was the high scatter observed on the reflected pressure histories measured by the pressure sensors.



a b

Figure 4. (a) Reflected pressure histories of two detonations. (b) Samples recovered after the explosion tests.

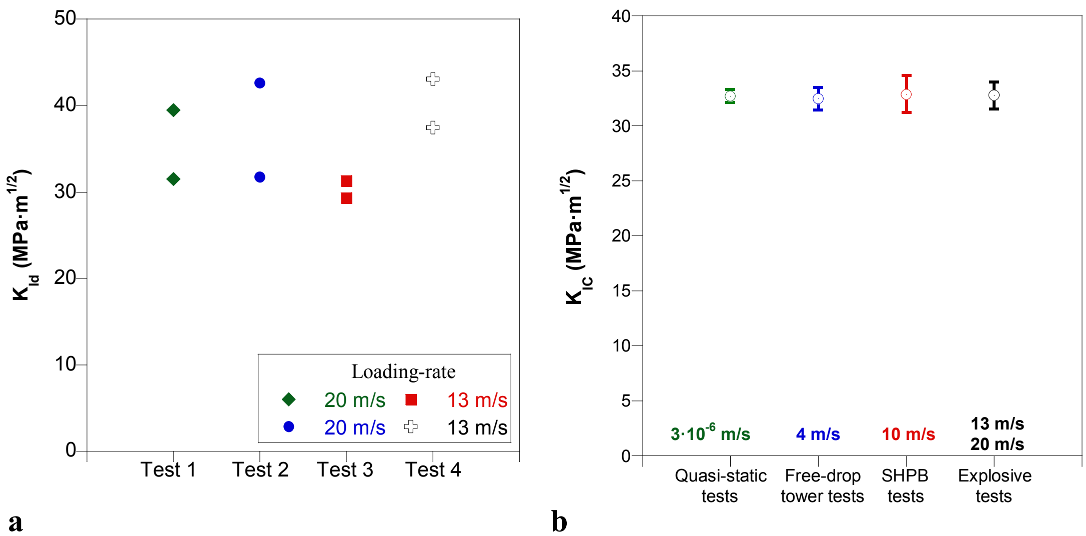


Figure 5. (a) Dynamic fracture-initiation toughness for 7017-T73 aluminium alloy under impulsive loadings. (b) Mean values and their standard deviations of the dynamic fracture-initiation toughness for 7017-T73 aluminium alloy at different loading-rates.

CONCLUSIONS

A new experimental device was designed and developed for the purpose of performing fracture toughness tests under impulsive loadings. A rate-independent alloy, a 7017-T73 aluminium alloy, was selected in order to validate such a device. Eight three-point bending tests were carried out in four different detonations. Such experiments provided the same value of the dynamic fracture-initiation toughness of the 7017-T73 aluminium alloy than the experiments previously performed at lower loading-rates.

In the light of the obtained results, the test procedure under explosive conditions was validated. That is to say, the experimental procedure allowed determining of the dynamic fracture-initiation toughness under impulsive loadings to a sufficiently accurate degree.

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REFERENCES

1. ASTM E399-12e3. *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials*. Book of ASTM Standards Volume 03.01.
2. Rittel, D., Maigre, H., Bui, H.D. 1992. "A new method for dynamic fracture toughness testing," *Scripta Metallurgica et Materialia*, 26: 1593-1598.
3. Weisbrod, G., Rittel, D. 2000. "A method for dynamic fracture toughness determination using short beams," *International Journal of Fracture*, 104:89-103.
4. Anderson, D. D., Rosakis, A. J. 2005. "Comparison of three real time techniques for the measurement of dynamic fracture initiation toughness in metals," *Engineering Fracture Mechanics*, 72:535-555.
5. Gálvez, F., Cendón, D., García, N., Enfedaque, A., Sánchez-Gálvez, V. 2009. "Dynamic fracture toughness of a high strength armor steel," *Engineering Failure Analysis*, 16:2567-2575.
6. Prasad, K., Kamat, S. V. 2010. "Dynamic fracture toughness of a near alpha titanium alloy Timetal 834," *Journal of Alloys and Compounds*, 491:237-241.
7. Dai, F., Chen, R., Xia, K. 2010. "A semi-circular bend technique for determining dynamic fracture toughness," *Experimental Mechanics*, 50:783-791.
8. Fengchun, J., Ruitang, L., Xiaoxin, Z., Vecchio, K. S., Rohtgi, A. 2004. "Evaluation of dynamic fracture toughness K_{Id} by Hopkinson pressure bar loaded instrumented Charpy impact test," *Engineering Fracture Mechanics*, 71:279-287.
9. Alexopoulos, N. D., Stylianos, A., Campbell, J. 2013. "Dynamic fracture toughness of Al-7Si-Mg (A357) aluminum alloy," *Mechanics of Materials*, 58:55-68.
10. Yokoyama, T. 1993. "Determination of dynamic fracture-initiation toughness using a novel impact bend test procedure," *Journal of Pressure Vessel Technology*, 115:389-397.
11. Rubio, L., Fernández-Sáez, J., Navarro, C. 2003. "Determination of dynamic fracture-initiation toughness using three-point bending tests in a modified Hopkinson pressure bar," *Experimental Mechanics*, 43:379-386.
12. Rubio-González, C., Gallardo-González, J. A., Mesmacque, G., Sánchez-Santana, U. 2008. "Dynamic fracture toughness of pre-fatigued materials," *International Journal of Fatigue*, 30:1056-1064.
13. Rodríguez, J., Navarro, C., Sánchez-Gálvez, V. 1994. "Some corrections to the data analysis of the dynamic tensile tests in the Hopkinson bar," *Journal de Physique IV*, 4(8):83-88.
14. Pérez-Martín, M.J., Erice, B., Gálvez, F. 2014. "On the loading-rate dependence of the Al 7017-T73 fracture-initiation toughness," *Procedia Materials Science*, 3C:1026-1031.
15. Morales-Alonso, G., Cendón, D. A., Gálvez, F., Erice, B., Sánchez-Gálvez, V. 2011. "Blast response analysis of reinforced concrete slabs: experimental procedure and numerical simulation," *Journal of Applied Mechanics*, 78:051010-1-051010-12.
16. Morales-Alonso, G., Cendón, D. A., Gálvez, F., Erice, B., Sánchez-Gálvez, V. 2011. "Blast response analysis of reinforced concrete slabs: experimental procedure and numerical simulation," presented at the 26th International Symposium on Ballistics, September 12-16, 2011.
17. Morales-Alonso, G. 2013. *Experimental and numerical analysis of reinforced concrete elements subjected to blast loading*. PhD thesis. Technical University of Madrid.