

DYNAMIC PROPERTIES OF CLAY BRICK AT DIFFERENT STRAIN RATES

J. M. Pereira¹, A. Dias² and P. B. Lourenço³

¹ PhD Student, ISISE – Institute for Sustainability and Innovation in Structural Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal, jpereira@civil.uminho.pt

² MSc Student, Department of Civil Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal, a54293@alunos.uminho.pt

³ Full Professor, ISISE – Institute for Sustainability and Innovation in Structural Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal, pbl@civil.uminho.pt

ABSTRACT

Investigation of the dynamic properties of construction materials is critical for structural engineering. The strain rate effect influences the properties on most constructions materials. This effect on materials such as concrete or steel has been intensively investigated. However, such studies on masonry materials such as clay bricks cannot be found in the open literature easily. Understanding the strain rate effect on masonry materials is important for proper modelling and design of masonry structures under high velocity impacts or blast loads. This work aims to study the behaviour of clay brick in compression at different strain rates. A Drop Weight Impact Machine will be used on clay brick specimens at different heights and weights introducing different levels of strain rate, ranging from 4 s^{-1} to 199 s^{-1} . The strain rate effect on the ultimate strength, young's modulus and strain at ultimate strength will be determined from the experimental results. Empirical relations of dynamic increase factors (DIF) for these material properties will be presented.

KEYWORDS: clay bricks, impact, drop weight, strain rate, DIF

INTRODUCTION

Different loading conditions lead to different strain rates. Quasi-static loading produce strain rates of around 10^{-5} s^{-1} , while impacts and blast loading produce strain rates of well over 10^0 s^{-1} . When subjected to dynamic loading conditions materials can have a different behaviour when compared with their static behaviour (Meyers, 1994; Hiermaier, 2008; Ngo et al, 2004; Stavrogin and Tarasov, 2001). Current research work on masonry structure response and damage under impact and blast loading assume static masonry properties (Baylot et al, 2005; Moreland et al, 2005). This can lead to an inaccurate prediction of masonry structure damage and fragmentation.

Construction materials such as concrete or reinforcement bars have been studied under the strain rate effect (Grote et al, 2001; Malvar, 1998) with this effect being already introduced into some standards such as CEB-FIP (1990) or TM 5-1300 (1990). However, very limited studies can be found in the open literature on masonry materials such as clay bricks or mortar. Recently Hao and Tarasov (2008) conducted an experimental study under dynamic uniaxial compression using a Triaxial Static-Dynamic Testing Machine. The specimens were cylindrical with a height of 78 mm and 38 mm of diameter and a total of 16 specimens of clay brick were tested under dynamic

conditions, with strain rates varying from 0.09 s^{-1} to 160 s^{-1} . It was reported a DIF for the ultimate strength of around 2.3 and 1.12 for the DIF of the ultimate strain, for a strain rate of 150 s^{-1} , regarding the young's modulus a DIF of 1.95 was reported for the same level of strain rate.

There is also a study presented by Burnett et al (2007) using a Split Hopkinson Pressure Bar on masonry joints to dynamic tensile loading. The strain rates of the tests ranged from 0.89 to 1.52 s^{-1} . The average tensile dynamic increase factor (DIF) of the masonry joint at a strain rate of 1 s^{-1} was found to be 3.1. As stated by the authors the results obtained in the study are the masonry composite properties under dynamic tensile loading. The strain effects on the individual components of masonry, brick and mortar, are not easily found in the open literature.

In this work, more than 70 brick specimens were prepared for dynamic uniaxial compression tests at different strain rates. The tests were conducted with a Drop Weight (DW) tower available at the Mechanical Engineering Department in the University of Minho. This equipment consists of a “hammer” with a certain mass being released at a chosen height. Authors like Islam and Bindiganavile (2011), Zhang et al (2008) and Banthia et al (1989) have used this kind of testing apparatus to investigate in influence of the strain rate effect on different materials.

These tests were used to study the behaviour of handmade clay brick under increasing strain rates. They were compared with an experimental static campaign previously developed by Sánchez (2007) on the same type of handmade clay bricks. Empirical relations for the material properties under different strain rates were developed and can be used to estimate the dynamic properties of the same kind of material under different strain rates.

BRICK SPECIMENS

With the objective of reproducing old Portuguese masonry constructions, the brick used was from Galveias, a village located in the central part of Portugal where handmade bricks can still be found. Brick specimens were prepared from a number of solid handmade clay brick. Realistically no two bricks are the same; however they are assumed to be of the same type with very similar properties.

The dimensions of the test specimens must be such that: a) ensure a complete representation of the material; b) maintain a proper height to cross section ratio to reduce the friction effects; and c) reduce the effect of inertia and non-uniform stress and strain in the specimen. The “Galveias” brick (Figure 1a) measured $20 \times 10 \times 5 \text{ cm}$ in dimensions and the test specimens measured $7 \times 3 \times 3 \text{ cm}$ (Figure 1b). From each “Galveias” brick five specimens were prepared. The test specimens were cut from the original brick by means of a disk cutting machine (Figure 2a). After cutting, the brick specimens were left to dry for a 24-hour curing period in laboratory air.

Prior to testing, the edges were ensure to be intact and the bearing surfaces at both ends of each specimen were ground to be flat and parallel to each other. This was achieved by means of using a grinding machine (Figure 2b). When the necessary preparation works were completed the specimens were left to dry in a ventilated oven (Figure 3c) at $105 \text{ }^\circ\text{C}$ until reaching constant mass. When constant mass were achieved they were moved to a non-ventilated oven at $40 \text{ }^\circ\text{C}$ and were kept there almost until testing, removed only 1 hour before testing. This procedure followed the recommendations of the NP EN 772-1, Portuguese standards.

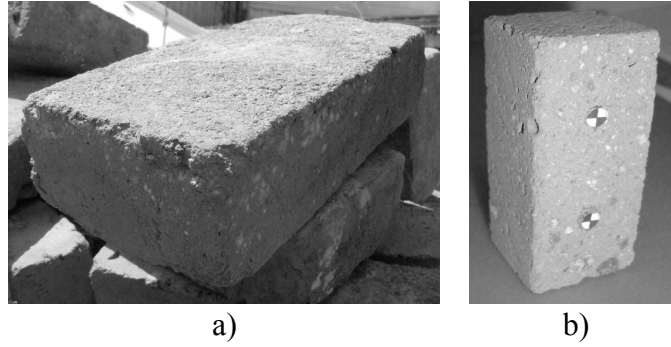


Figure 1: Clay brick: a) Galveias brick (20×10×5 cm); b) Test specimen (7×3×3 cm)

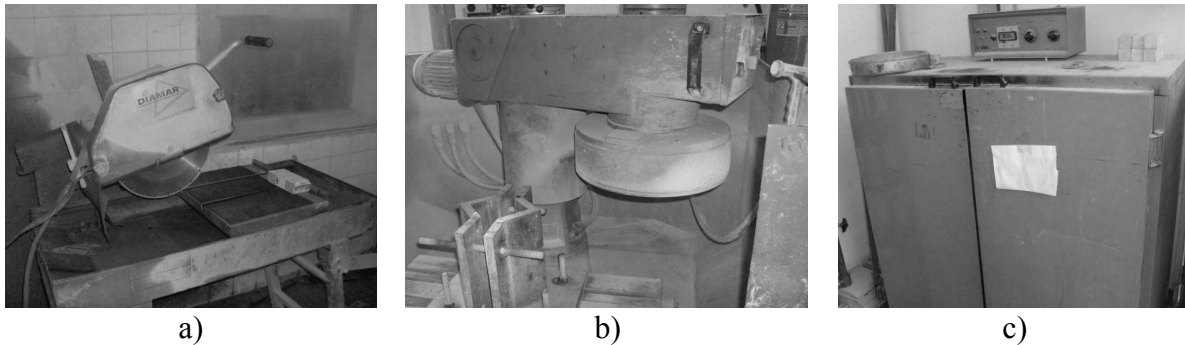


Figure 2: Specimen preparation: a) cutting machine; b) grinding machine; c) ventilated oven

Before testing, two targets were glued to the specimen surface (Figure 1b) in order to perform a tracking of their position in time using video equipment. These two points allow registering the variation in length, axial strain, of the specimen during the test.

EXPERIMENTAL SETUP

The Drop Weight (DW) tower available at the Mechanical Engineering Department in the University of Minho allows weights between 60 and 150 kg and up to 9 meters drop height. Figure 3 shows a schematic of the test setup. It consists of a dropt tower with moving “hammer” where can be attached additional masses (Figure 4a). At the bottom a base metal plate with a load cell holds the specimen. The load cell used is a VETEK C2S (Figure 4b) model connected to a National Instruments (NI) acquisition chassis and the acquisition is controlled through personalised software in LabView, allowing acquisition frequencies of up to 100 kHz. There is also an accelerometer placed in the “hammer” and it is connected to the same NI chassis. Both acquisition systems are used to register the compression force in time. To register the deformations it is used fast video equipment. A PHOTRON APX-RS (figure 4c) is used to register the deformations, this camera allows up to 250 000 fps and is it connected to its own acquisition software and equipment. The movie acquired through the FastCam equipment needs to be analysed with tracking software in order to determine the relative position of the targets (Figure 1b) during the test. To perform this analyses the software TEMA Automotive was used.

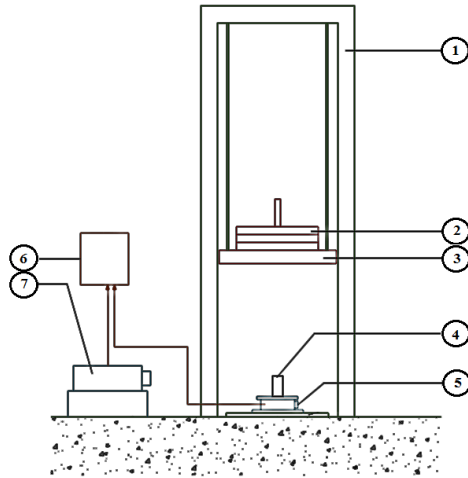


Figure 3: Schematic of the test setup: 1) DW tower; 2) additional masses; 3) hammer; 4) test specimen; 5) load cell; 6) acquisition system; 7) fastcam video

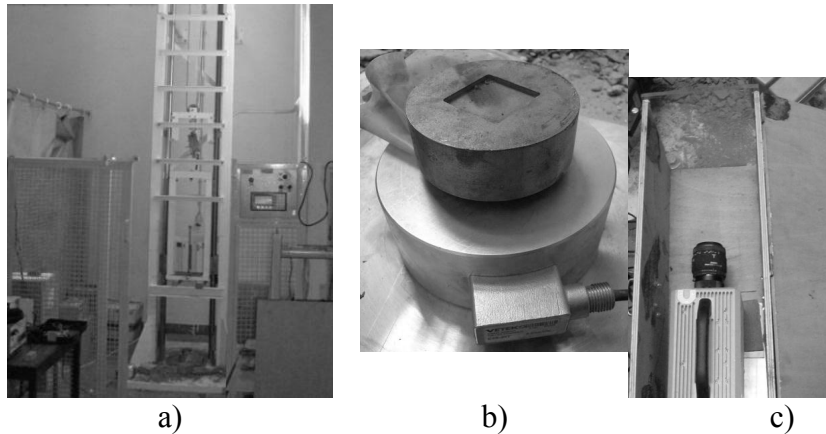


Figure 4: Testing equipment: a) DW tower, b) load cell with specimen support base; c) PHOTRON APX-RS

TEST RESULTS AND DISCUSSION

A total of 99 tests under uniaxial compression were performed. Some of the test (29) did not give any good results. Only 70 results are presented and used in the present analysis. Figure 5 shows some time-histories examples for stress (Figure 5a) and strain (Figure 5b). In Figure 6 it can be seen some stress-strain relations for different levels of strain rate. The material properties, Ultimate Strength, Strain at ultimate strength and Young's Modulus are derived from these relations. The strain rate was assumed as constant for each test and taken as the gradient of the strain-time curve (Hao and Tarasov, 2008). Part of the results is summarized in Table 1.

Previous studies on similar materials such as concrete and rock indicate a general increase in the material's properties with the strain rate. It is also noted that the behaviour of the Ultimate Strength, Young's Modulus and Strain at Ultimate Strength with the strain rate follows a log-linear curve for strain rates over 4 s^{-1} (Grote et al, 2001; Hao and Tarasov, 2008; Zhao et al, 1999).

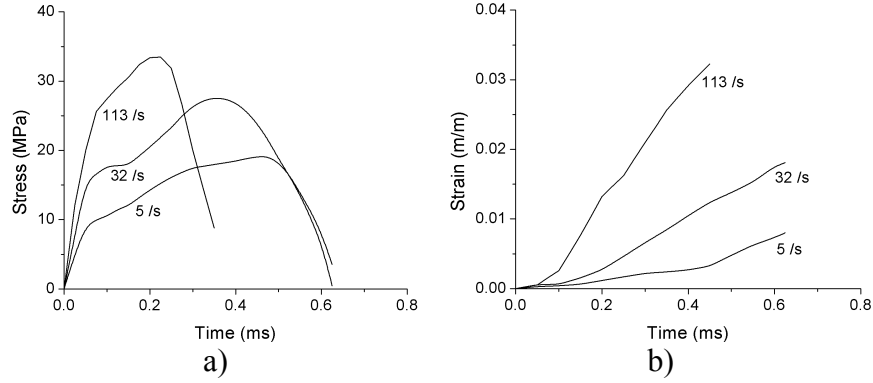


Figure 5: Time-histories: a) Stress-time; b) Strain-time

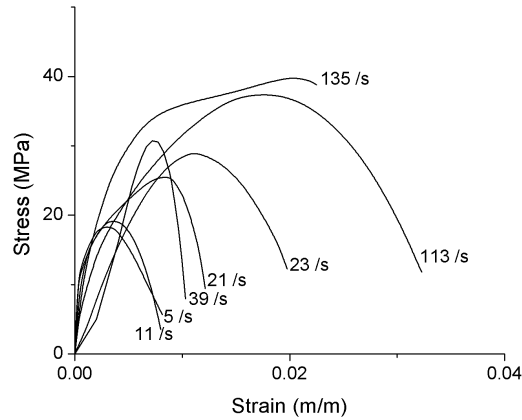


Figure 6: Stress-Strain curves at different strain rates

As expected all these properties increase with the strain rate. All three material's properties can be modelled as a log-linear function for strain rates over 4 s^{-1} . For a strain rate of 200 s^{-1} there is a corresponding DIF of 2.58, 1.94 and 2.02 for the Ultimate Strength, Young's Modulus and Strain at Ultimate Strength, respectively.

From the results, the DIF for the materials properties, which is the ratio between the dynamic and static property, are derived as a function of strain rate. Figures 7 to 9 shows the DIF of material's Ultimate Strength, Young's Modulus and Strain at Ultimate Strength, respectively, as a function of strain rate.

The best-fitted equation of DIF as a function of the strain rate for the Ultimate Strength can be derived as:

$$DIF(\sigma_u) = 0.3224 \cdot \ln(\dot{\epsilon}) + 0.8724, \quad 4 < \dot{\epsilon} < 200 \text{ s}^{-1} \quad (1)$$

For the Young's Modulus:

$$DIF(E) = 0.1921 \cdot \ln(\dot{\epsilon}) + 0.9196, \quad 4 < \dot{\epsilon} < 200 \text{ s}^{-1} \quad (2)$$

For the Strain at Ultimate Strength:

$$DIF(\varepsilon_u) = 0.2606 \cdot \ln(\dot{\varepsilon}) + 0.6419, \quad 4 < \dot{\varepsilon} < 200 \text{ s}^{-1} \quad (3)$$

Table 1: Test Results

Strain rate (s ⁻¹)	Ultimate Strength, σ_u (MPa)	DIF (σ_u)	Young's Modulus, E (GPa)	DIF (E)	Strain at ultimate strength, ε_u (m/m)	DIF (ε_u)	Specimen (#)
Quasi-static	15.30	-	3.28	-	0.00120	-	Static ref.
4	22.37	1.462	4.85	1.479	0.00118	0.980	2
5	23.38	1.528	4.71	1.436	0.00147	1.223	5
5	21.74	1.421	3.94	1.201	0.00163	1.362	8
7	21.88	1.430	3.43	1.045	0.00170	1.417	10
11	25.04	1.636	4.68	1.428	0.00123	1.023	12
11	22.05	1.441	5.39	1.643	0.00132	1.101	19
18	28.10	1.837	5.11	1.557	0.00126	1.050	22
21	28.57	1.867	5.63	1.716	0.00222	1.849	29
22	26.42	1.727	3.88	1.182	0.00182	1.513	35
29	28.94	1.892	4.51	1.374	0.00242	2.020	37
34	35.90	2.346	5.30	1.616	0.00154	1.282	45
39	36.61	2.393	6.47	1.971	0.00232	1.930	49
40	32.17	2.103	4.47	1.362	0.00157	1.304	58
42	36.93	2.414	6.01	1.832	0.00132	1.100	62
54	35.94	2.349	6.90	2.104	0.00173	1.439	67
57	37.64	2.460	6.84	2.085	0.00241	2.010	73
73	32.74	2.140	5.19	1.581	0.00253	2.110	80
80	34.89	2.281	4.74	1.445	0.00266	2.217	82
176	33.87	2.214	6.21	1.893	0.00269	2.240	93

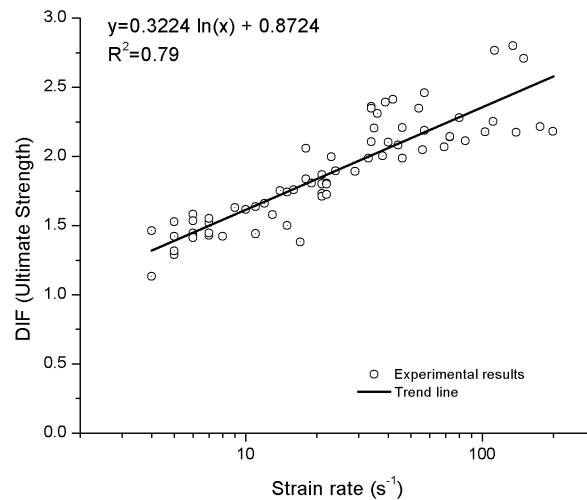


Figure 7: DIF for Ultimate Strength

Compressive Ultimate Strength is sensitive to the strain rate as seen before. In this work the behaviour captured follows the same log-linear curve of previous studies, and for clay brick Hao

and Tarasov (2008) reported a DIF for compressive Ultimate Strength for strain rate 150 s^{-1} of 2.31. In this, work for the same strain rate, a DIF of 2.49 is obtained.

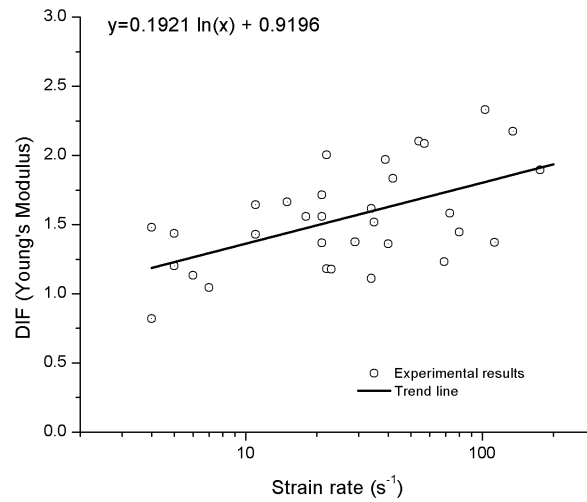


Figure 8: DIF for Young's Modulus

The Young's Modulus is less sensitive to the strain rate for materials such as concrete (CEB-FIP, 1990) and for clay brick this remains true (Hao and Tarasov, 2008). In the present work the same conclusion can be taken from the results as it is the studied property with the lowest DIF for higher strain rate. Hao and Tarasov (2008) reported a DIF for the Young's Modulus of clay brick under the strain rate 150 s^{-1} of 1.95 which is similar with the one from this work at the same strain rate, 1.88.

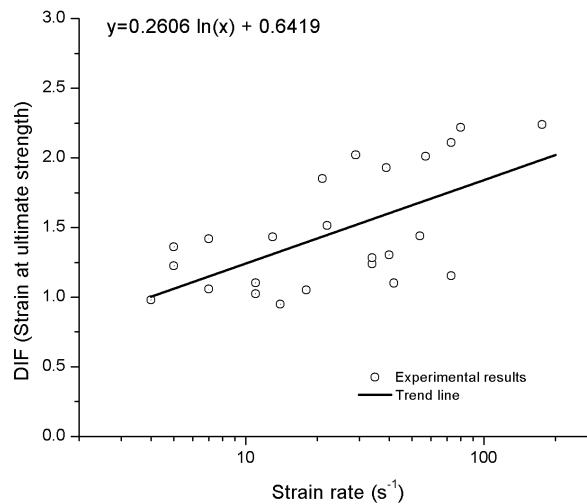


Figure 9: DIF for Strain at Ultimate Strength

Comparing the results from the Strain at Ultimate Strength with previous work on similar materials, it can be seen that this work was able to predict the same log-linear behaviour (CEB-FIP, 1990; Hao and Tarasov, 2008). However, Hao and Tarasov (2008) reported a much less sensitive increase of the strain with the strain rate for clay brick. For strain rate 150 s^{-1} the same authors presented a DIF for Strain at Ultimate Strength of 1.12. With the results presented in the

work, for the same strain rate, a DIF of 1.95 is achieved. Although it has been observed that the Strain at Ultimate Strength of concrete, rock or brick increase with the strain rate, very few empirical relations are available in the literature.

CONCLUSIONS

This work describes an experimental campaign on the strain rate effect on handmade clay bricks, using a Drop Weight Impact Machine. The obtained strain rate ranged from 4 s^{-1} to 199 s^{-1} . It was found that the Ultimate Strength, Young's Modulus and Strain at Ultimate Strength of handmade clay bricks increase with strain rate leading to DIFs in the range of 2 to 3 for strain rates of 200 s^{-1} . Not including this effect in the design and modelling of masonry structures can lead to inaccurate prediction of the structures behaviour. However, very limited dynamic material properties of masonry are available in the open literature.

Empirical relations, with strain rate, for Ultimate Strength, Young's Modulus and Strain at Ultimate Strength were derived from the results and presented. It was shown that the behaviour of this kind of brick is similar to other geomaterials such as concrete or rock. Comparing these results with a previous work using a Triaxial Testing Machine (Hao and Tarasov, 2008) it can be seen a good agreement in the results for the Ultimate Strength and the Young's Modulus. For the Strain at Ultimate Strength there is considerable difference in the results. These empirical relations can be used to model masonry structures under dynamic loading conditions.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from the research project CH-SECURE (PTDC/ECM/120118/2010) funded by the Foundation for Science and Technology (FCT).

REFERENCES

1. Meyers, M. A. (1994) "Dynamic Behavior of Materials". Library of Congress Cataloging in Publication Data.
2. Hiermaier, S. J. (2008) "Structures Under Crash and Impact - Continuum Mechanics, Discretization and Experimental Characterization". Springer Science+Business Media, LLC. Freiburg, Germany.
3. Ngo, T., Mendis, P., Hongwei, M., Mak, S. (2004) "High strain rate behaviour of concrete cylinders subjected to uniaxial compressive impact loading". Proceedings of 18th Australasia Conference on the Mechanics of Structures and Materials, Australia.
4. Stavrogin, A. N. and Tarasov, B. G. (2001) "Experimental physics and rock mechanics", Balkema.
5. Baylot, J. T., Bullock, B., Slawson, T. R., Woodson, S. C. (2005) "Blast response of lightly attached concrete masonry unit walls", Journal of Structural Engineering, ASCE, Vol. 131, No 8, pp. 1186-1193.
6. Moreland, C., Hao, H., Wu, C. Q. (2005) "Response of retrofitted masonry walls to blast loading", Proceedings of the 6th Asia-Pacific Conference on Shock and Impact Loads on Structures, Perth, Western Australia.

7. Grote, D. L., Park, S. W., Zhou, M. (2001) "Dynamic behaviour of concrete at high strain rates and pressures: I. Experimental characterization", *International Journal of Impact Engineering*, Vol. 25, pp. 869-886.
8. Malvar, L.J. (1998) "Review of Static and Dynamic Properties of Steel Reinforcement Bars", *ACI Material Journal*, Detroit, Michigan, Vol. 95, pp 609-616.
9. Comité Euro-International du béton (1990), "CEB-FIP Model Code 1990", Redwoods Books, Trowbridge, Wiltshire, UK.
10. TM 5-1300 (1990), "The Design of Structures to Resist the Effects of Accidental Explosions", Technical Manual, US Department of the Army, Navy, and Air Force, Washington DC.
11. Hao, H., Tarasov, B. G., (2008) "Experimental study of dynamic material properties of clay brick and mortar at different strain rates", *Australian Journal of Structural Engineering*, Vol. 8, pp. 117-132.
12. Burnett, S., Gilbert, M., Molyneaux, T., Tyas, A., Hobbs, B., Beattie, G. (2007) "The response of masonry joints to dynamic tensile loading", *RILEM Journal of Materials and Structures*, Vol. 40, pp. 517-527.
13. Islam, M. T., Bindiganavile, V. (2011) "The impact resistance of masonry units bound with fibre reinforced mortars", *Construction and Building Materials*, Vol. 25, pp. 2851-2859.
14. Zhang, X.X.; Ruiz, G.; Yu, R.C. (2008), "A New Drop Weight Impact Machine for Studying Fracture Process in Structural Concrete", *Anales de Mecánica de la Fractura* 26, Vol. 2, pp. 513-518.
15. Banthia, N., Yan, C., Sakai, K., (1989) "Impact resistance of fiber reinforced concrete at subnormal temperatures", *Cement and Concrete Composites*, Vol. 20, pp. 393-404.
16. Sánchez, I. B. (2007) "Strengthening of arched masonry structures with composites materials", PhD thesis, Chapter 3, University of Minho, Portugal.
17. Norma Portuguesa NP EN 772-1 (2002). "Métodos de ensaios de blocos para alvenaria (Parte 1: Determinação da resistência à compressão)", in Portuguese.
18. Zhao, J., Li, H. B., Wu, M. B., Li, T. J. (1999) "Dynamic uniaxial compression tests on granite", *International Journal of Rock Mechanics and Mining Sciences*, Vol. 36, pp 273-277.