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Investigating the fracture behavior of Portland limestone: an experimental study

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Abstract

An experimental investigation of the mechanical and fracture characteristics of the 'Grove Whitbed' Portland limestone is undertaken with the aim to enhance understanding of the structural behavior of this natural building stone, commonly used in both new and restoration projects in Edinburgh, Scotland. A series of appropriate prismatic specimens, bearing a machined notch at their mid-span and comprising combinations of three different geometries (span/depth ratios) and three different sizes (span lengths) were subjected to three-point bending testing. The effect of specimen shape and size on flexural strength, deflection at mid-span, crack mouth opening displacement (CMOD) and fracture energy was studied. Despite the scattering of results which is significant but common in studies of the mechanical behavior of similar geomaterials, trends observed comprise (a) the negative correlation between the flexural strength of Portland limestone test specimens and their span lengths for all three shapes and (b) the positive correlation between fracture energy and specimen size. Conclusions drawn are in good agreement with similar ones for other quasibrittle materials and contribute to the assessment of the fracture behavior of full size structural members that are often beyond the range of possible failure testing.

Keywords: Natural building stones; Portland limestone; Mechanical properties; Size effect; Shape effect; Fracture energy

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1. Introduction

Scotland's historic environment is an essential part of the country's cultural background and its economy. Scotland has a long history of building with stone and is one of the countries with the richest legacies of traditional and historic buildings in the UK, with around 450,000 traditionally constructed buildings including castles, bridges, dwelling houses and churches (Historic Environment Scotland 2017). Some of these are internationally iconic structures of historical and cultural heritage.

The city of Edinburgh is an excellent showcase of natural building stone's use as a construction material, being extensively utilized throughout the city since the early 11th century and earning the city the alias 'the Grey Athens of the North' (Fig. 1). Various types of sandstone, such as Dunhouse, Corsehill and Craigleith, were easily available due to the abundance of quarries located locally in the Lothians and Fife (Fairhurst et al. 1999). Eventually, during the construction of the 'New Town' district of Edinburgh from the 18th to the 20th century, the local sandstone supplied became exhausted paving the way for new types of stone to be imported into the city from further afield in Britain, such as limestone, granite and dolerite. This added further depth to the architecture of the city (Fig 2a,b).

The rehabilitation and conservation of historic stone masonry buildings is a matter of great importance around the world, as it is related with the need to improve and extend the life of a structure for new conditions of use and to protect our cultural heritage. Since the conclusion of World War 1, the use of natural building stone as a primary construction material declined in place of cheaper, easier to produce materials such as concrete (Hyslop et al. 2006). Even though nowadays most projects involving natural building stones are restoration projects, there has been a renaissance in their use as a primary building material in the last 30 years (Fig. 2c), attributed to both architectural requirements and public yearning for buildings that are not just functional but also aesthetically pleasing.

For the purpose of definition of failure criteria for natural building stones used in new as well as restoration projects, their mechanical behavior and fracture characteristics need to be experimentally investigated. The geometry and the shape of specimens proposed by standards relevant to brittle geomaterials differ, concerning both their shape and size. In any case, laboratory space and equipment restrictions together with prohibitive costs for large scale testing, make the design of large elements and structures dependent inevitably on extrapolation from test results on much smaller laboratory specimens.

Fig. 1. (a) National Gallery; (b) Royal Scottish Academy, The Mound.

Fig. 2. (a) The Royal Society of Edinburgh; (b) St. Mary's Cathedral; (c) National Museum of Scotland.

Design codes do not yet include explicit guidance regarding the transition from laboratory results based on smaller scale specimens to parameters suitable for the design of full size structural elements. This is attributed to the - evident in the literature - lack of unanimous scientific approach and generally accepted theory concerning the laws governing this transition, making regulatory bodies reluctant to change currently used empirical or semi-empirical formulas based on curve fitting to the experimental results (Bažant and Yavari 2005).

Interest in the size effect goes many centuries back, with the observation that the nominal strength of structural elements changes by scaling their size been made by Leonardo Da Vinci (1883). The primal scaling idea by Galileo (1638) introducing the concepts of stress and strength was much later soundly questioned by the statistical weakest-link theory by Fisher and Tippett (1928), further developed by Weibull (1939). Limitations to the use of the statistical approach were posed due to discrepancies emerging from various experiments first conducted in concrete by Walsh (1972). Nowadays, two approaches are widely encountered in the literature: the deterministic energetic theory by Bazant (1984), based on the observation that failure of quasi-brittle materials is characterized by both energy and stress quantities and the theory of crack fractality as described by Carpinteri (1994) and Carpinteri et al. (2003), associating the size effect with the fractal nature of crack surfaces.

In this context, this experimental study focuses on the influence of specimen shape and size on the mechanical and fracture behavior of Portland limestone, a natural building stone widely used in Edinburgh. Consideration of relevant studies on marble (Vayas et el. 2009, Kourkoulis et al. 2002) and porous stone of Kefalonia, Greece (Kourkoulis and Ganniari-Papageorgiou 2010) has paved the way for this particular investigation comprising an experimental protocol of three-point bending tests, aiming at shedding light on the dependence of flexural strength, deflection at mid-span, crack mouth opening displacement and fracture energy on specimen size and shape. This is a contribution to the wider investigation of the problem but also of applicability for the optimisation of the design and rehabilitation of load-bearing structural members like lintels and sills, loaded in position in a similar way.

2. The experimental protocol

2.1. The material and the specimens

'Grove Whitbed' Portland limestone, originating from the Jurassic Period, is a grain supported biomicrite consisting of rounded micritic ooliths with concentric structures of diameters ranging from 50μm to 300μm, irregular quartz grains with a nominal size of 100μm and a large quantity of bioclasts which range in size from 5μm to 20μm (Leary 1983). The relatively large Turreted Gastropods (fossilised shells) and clam shells found within Portland Limestone are responsible for the voids (nominal size of 100μm) that can be found throughout the stone, as the removal of these shell fragments due to percolating rain over time left behind what can be observed as holes.

Portland Limestone has a creamy/white hue, which can be darkened by clusters of grey shell fragments, scattered throughout the stone. It has a coarse texture and inhomogeneous/porous properties which contributes to the stone having a low level of durability, with a weathering rate of 3mm to 4mm per 100 years expected, particularly at the edges of stonework (Leary 1983). A selection of Portland Limestone's material properties was experimentally determined (Table 1), prior to this particular study focusing on the size- and shape- effects (Stewart 2016).

Table 1. Mechanical characterisation of Portland limestone.

Portland Limestone Material Properties	
Apparent Density (kg/m^3)	1955.14
Density of solids (kg/m^3)	3078.42
Open Porosity (%)	15.87
Total Porosity (%)	36.49
Modulus of Elasticity (3 PB) (MPa)	8340.54
Modulus of Elasticity (Pundit Test) (MPa)	11820.89
Compressive Strength (MPa)	36.90
Flexural Strength (3 PB) (MPa)	4.91
Flexural Strength (4 PB) (MPa)	4.13

Within the scope of this paper, the experimental investigation comprised three-point bending tests on specimens with span/height ratios of 5/2, 4 and 6, bearing a 4mm wide machined notch at their mid-span for 1/3 of their height. For each span/height ratio and a constant breadth of 40mm, three different sizes of specimen (span length = 200mm, 400mm and 800mm) were tested, with four repetitions each, in order to observe the influence of size as well as shape on flexural strength, deflection at mid-span, CMOD and fracture energy. The type of test and specimens' dimensions adopted (Table 2) were based on considerations of appropriate standards and publications (RILEM TC50-FMC 1985, Hillerborg 1983) and limitations regarding laboratory facilities and costs.

Table 2. Portland limestone test specimen specifications.

Span/Height Ratio	Length (mm)	Span (mm)	Height (mm)	Notch length (mm)
5/2	250	200	80	27
	450	400	160	53
	850	800	320	160
4	250	200	50	17
	450	400	100	33
	850	800	200	67
6	250	200	33	11
	450	400	66	22
	850	800	133	44

2.2. The experimental set-up

The experimental programme implemented by this project followed the principles described in BS EN 12372: 2006 (Natural stone test methods – Determination of flexural strength under concentrated load) and by RILEM Technical Committee 50-FMC (1985). All tests were performed at Edinburgh Napier University's 'Heavy Structures' laboratory.

The specimens were left to dry in a ventilated oven at 70±5ºC until a constant mass was achieved and then were stored at 20±5ºC to reach thermal equilibrium. Testing took place within 24 hours, using a stiff Instron Universal testing machine calibrated to EN12390 and in configuration as per Fig. 3, having the specimen's strong plane of anisotropy perpendicular to the direction of the applied load.

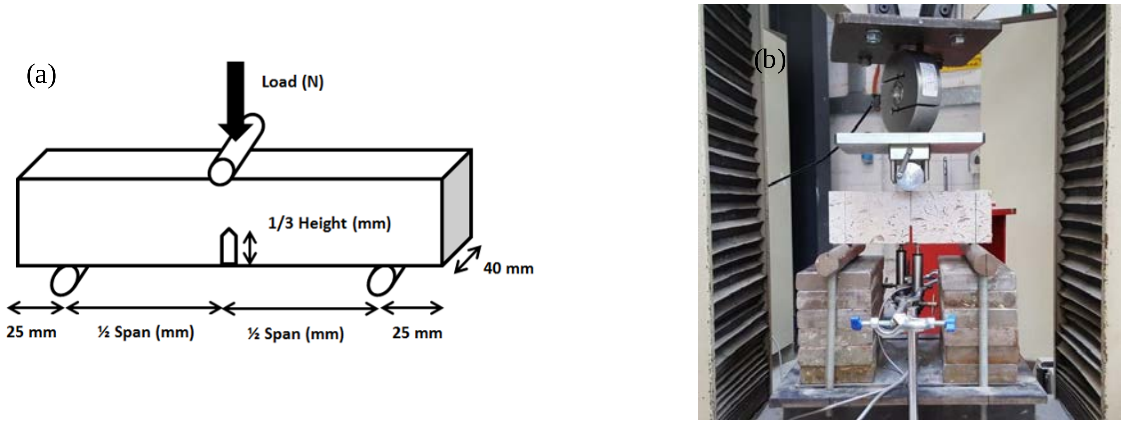

Fig. 3. (a) Three-point bending test configuration; (b) actual test set-up (200mm span).

A clip gauge was positioned across the notch on the specimen, attached to specialised brackets glued to either side, to record the Crack Mouth Opening Displacement (CMOD). Appropriately positioned Linear Variable Differential Transformers (LVDTs) were used to capture deflections at mid-span. Adopting a displacement-control procedure at testing, the loading rate applied was 0.1mm/min. Following this, the peak load was reached within approximately 2-3 minutes and, given our interest in the post-peak behavior of the material till the specimen can bear no load, the duration of each test was 8-10 minutes. Typical fractured specimens are shown in Fig. 4.

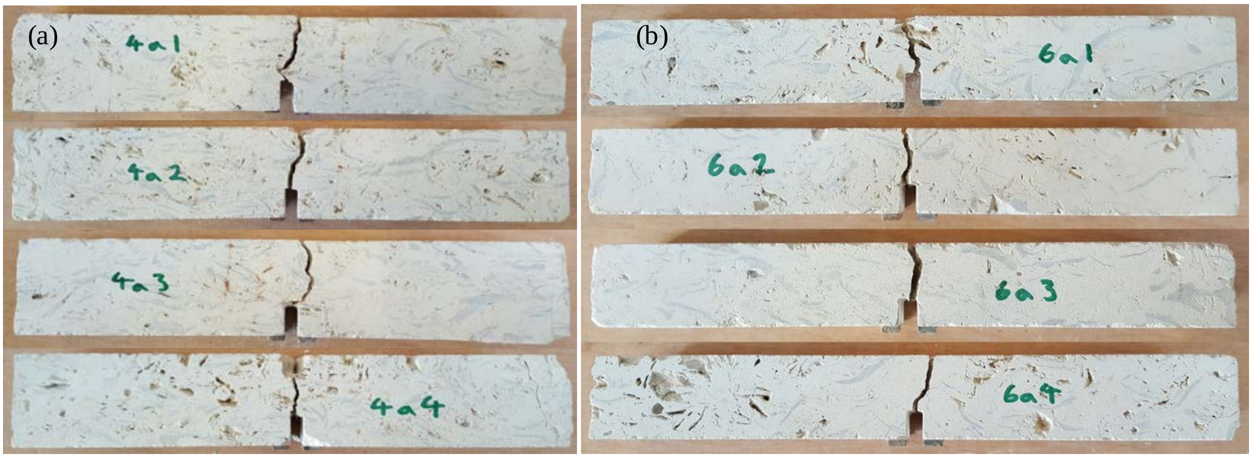

Fig. 4. Failure modes observed after testing for (a) 200mm span and span/depth=4; (b) 200mm span and span/depth=6.

3. Experimental Results

3.1. Typical results

Typical *load-deflection at midspan* and *load-CMOD* curves of Portland limestone specimens under three-point bending were directly derived from experimental recordings (Fig.5). A typical load-deflection curve consists of three distinct portions: up to the peak load the constitutive law is almost perfectly linear elastic. This region is abruptly terminated by a significant load drop which in turn leads to a third portion, characterized by a small slope, up to final disintegration of the specimens.

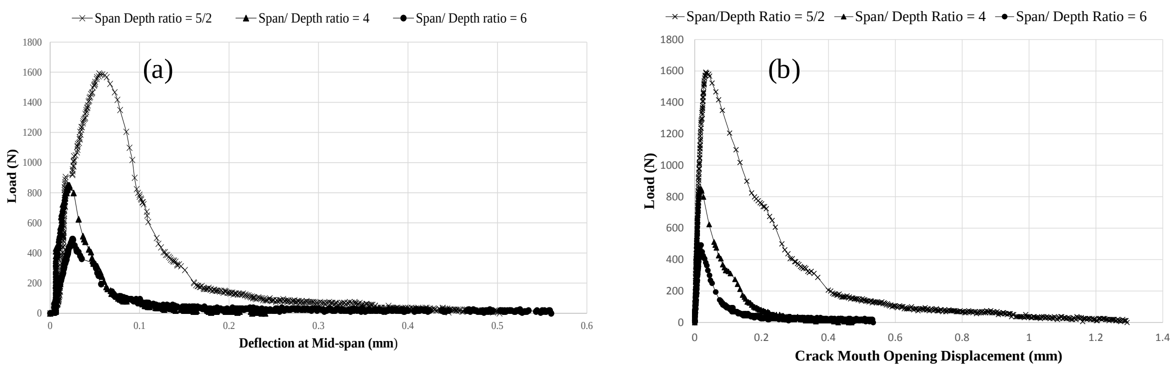

Fig. 5. (a) The load applied vs. deflection at mid-span for 200mm spans; (b) The load applied vs. CMOD for 200mm spans.

The flexural strength R_{tf} of each specimen was calculated according to the method proposed by BS EN 12372:2006 by application of the formula:

$$R_{tf} = \frac{3Fl}{2bh^2} \tag{1}$$

where F is the breaking load (N), l the span, b the breadth and h the height of specimen (all in mm).

Using concepts developed for concrete but applicable to other materials where the compressive strength is high compared to the tensile strength, Portland limestone's toughness and subsequently tensile fracture behavior were quantified by means of calculating the fracture energy per unit area of the fracture surface, G_F. The fracture energy can be determined by means of a stable bending test, provided that the fracture takes place along one reasonably well-defined plane and that energy absorption in other processes than tensile fracture is negligible (Hillerborg 1983). Considering the area W_0 below a *load-deflection at midspan* diagram that gives the energy supplied by the machine and making a correction for the amount of absorbed energy due to the weight of the beam/testing equipment between the supports, the fracture energy per unit area G_F is calculated as:

$$G_F = \frac{W_0 + mg \cdot \delta_0}{A_{\text{lig}}} \tag{2}$$

where δ_o is the deformation when the force has fallen to zero and A_{lig} is the projection of the fracture area on a plane perpendicular to the beam axis (ligament area). The summary of average results for parameters as outlined above is presented in Table 3:

Table 3: Summary of three-point bending tests results for Portland limestone.

Span/ Depth Ratio	Span (mm)	Fracture Energy (Nm/m^2)	Flexural Strength (MPa)	Deflection at Peak Load (mm)	CMOD at Peak Load (mm)
5/2	200	67.46	1.89	0.042	0.039
	400	95.30	1.76	0.103	0.066
	800	284.33	1.08	0.750	0.104
4	200	36.45	2.37	0.076	0.043
	400	40.12	1.84	0.076	0.043
	800	152.45	1.48	0.446	0.085
6	200	37.78	3.18	0.028	0.021
	400	49.27	1.82	0.089	0.029
	800	83.88	1.35	0.274	0.074

3.2. Combined results for the investigation of the size- and shape- effects

Completing the experimental program as detailed above, led to observations on average results regarding the influence of the specimens' geometry on key properties such as the deflection at mid-span and the CMOD at peak load, the flexural strength, the fracture energy and potential failure modes. For all three sets of span/depth ratios, there is a steep increase in deflections when the specimen span length increases to 800mm. The magnitude of this increased rate of deflection at mid-span increases as the test specimen's span/depth ratio decreases (Fig.6a). In terms of CMOD, apart from the case of a span/depth ratio equal to 4 with span lengths of 200mm and 400mm, where values remained constant, in general it was observed that CMOD values increase at an almost uniform rate as their span length increased (Fig. 6b). Larger values of CMOD were recorded as the span/depth ratio decreased.

In terms of flexural strength, the span/depth ratio, which appears to be most sensitive to changes in size, is the largest, 6. The test specimens with span/depth ratios of 5/2 and 4 present very similar outcomes to each other, which is the case also for the span/depth being 6, with span lengths 400mm and 800mm (Fig.7a). The values of fracture energy obtained from test specimens with span/depth ratios of 4 and 6 are very similar for spans 200mm and 400mm while those for span/depth ratio of 5/2 are significantly larger (Fig. 7b). Increasing fracture energy values for span/depth ratio of 5/2 and 4 appear to follow a bilinear law as test specimen size increases, while the span/depth ratio of 6 form a linear pattern. These findings are in good agreement with data existing in the literature, stating that fracture energy is directly influenced by the configuration of the test specimens (Malvar and Warren 1988).

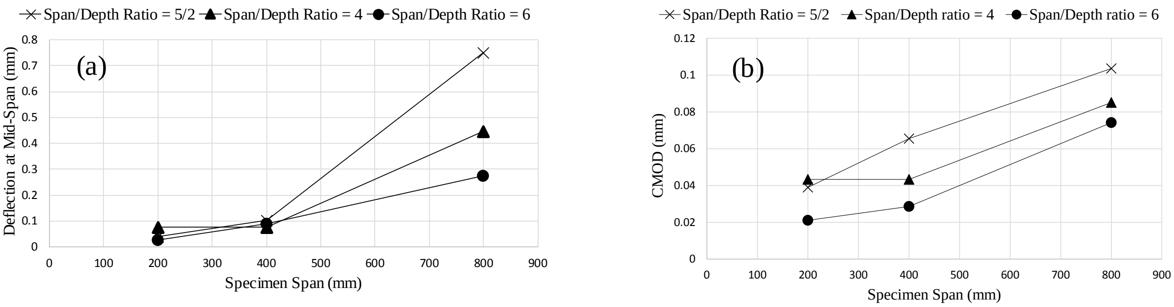

Fig. 6. (a) Deflection at mid-span vs. span length for all span/depth ratios; (b) CMOD vs. span length for all span/depth ratios.

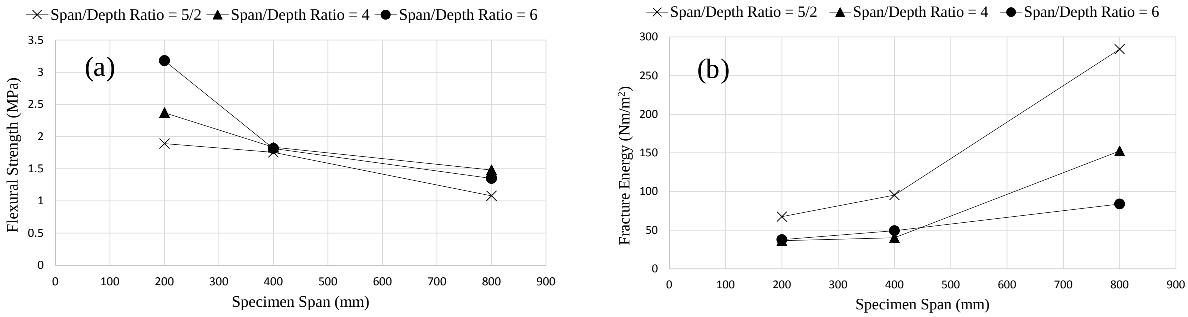

Fig. 7. (a) Flexural strength vs. span length for all span/depth ratios; (b) Fracture Energy vs. span length for all span/depth ratios.

Most of the specimens failed in a similar manner for all shapes, with cracks appearing to propagate from the tip of the notch and then veering slightly off-center (Fig.4). With the span/depth ratio of 6, there were occasions when the specimens failed off-center, with the crack starting at a random location between the notch and roller supports. Most irregular failure modes observed were attributed post-failure to the presence of relatively large mineral build-ups within the specimen that promoted failure planes around them.

4. Conclusions

The main objective of this research was to examine the effect that test specimen size and shape have on several key properties of Portland limestone, including deflection at mid-span at peak load, CMOD at peak load, flexural strength and, in particular, fracture energy. This was achieved by subjecting a batch of specimens, containing three different shapes (span over depth ratio) that came in three different sizes (spans), to a series of three-point bending tests at Edinburgh Napier University's Heavy Structures laboratory.

For the specimens tested, a bilinear relationship between the studied deflection and specimen span length was identified for span/depth ratios of 5/2 and 4, with a gentle positive gradient existing between span lengths of 200mm and 400mm, before a dramatic increase between span lengths of 400mm and 800mm. For test specimens with a span/depth ratio of 6, this deflection appeared to increase linearly with span length. It was also observed that this deflection appeared to be independent from the span/depth ratio of the specimens, for span lengths 200mm and 400mm but for span lengths at 800mm, it increased as the span/depth ratio decreased. A similar pattern of observations was made for the CMOD at peak load, leading to the conclusion that it appears likely for a critical specimen size to exist for Portland limestone, where the effect of specimen size and shape becomes more apparent.

A negative correlation between the flexural strength of Portland limestone specimens and their span lengths for all three shapes was observed, supporting the findings by Rokugo et al (1995). This was most evident for span/depth ratio of 6, with a significant decrease in flexural strength recorded between the span lengths of 200mm and 400mm.

The most noteworthy finding of this experimental study was the positive correlation between fracture energy and test specimen size. Between span lengths of 200mm and 400mm there is a gradual increase of fracture energy, before a significant rise when the span length gets to 800mm. For the span/depth ratio of 5/2, clearly larger values of fracture energy were recorded, indicating the dependence of fracture energy on test specimen size and geometry as supported by other studies (Malvar and Warren 1988).

For tests performed within the scope of this investigation, the variation of the strength and fracture energy with increasing specimen's size appears to be monotonic, a behavior that is commonly observed for concrete (del Viso et al. 2008) but not necessarily for a selection of other natural building stones (Kourkoulis and Ganniari-Papageorgiou 2010, Kourkoulis 2011, Vardoulakis and Kourkoulis 1997, Vardoulakis et al. 2002, Vardoulakis and Kaklis 2004, Kourkoulis et al.2005). Given the significant scattering of results for this kind of natural building stones and the limitations of a small-scale experimental study, definite conclusions for the size- and shape-effects cannot yet be drawn and more experimental evidence is required. The above requirement is imperative in an effort to fully explore the behavior laws covering transition from the scale of 'materials' to that of 'structural members' and choose accordingly specimens that are representative of Portland limestone's behavior and useful for design purposes.

References

Bažant, Z.P., 1984. Size effect in blunt fracture: concrete, rock, metal. J Eng Mech; 110:518-35.

Bažant, Z.P. and Yavari, A., 2005. Is the cause of size effect on structural strength fractal or energetic-statistical?. Eng Frac. Mech; 72, 1-31.

Carpinteri A., 1994. Fractal nature of material microstructure and size effects on apparent mechanical properties. Mech Mater; 18:89-101.

Carpinteri A., Chiaia A., Cornetti P., 2003. On the mechanics of quasi-brittle materials with a fractal microstructure. Eng Frac Mech; 70, 2321-49.

Da Vinci, L., 1883. Les Manuscripts de Léonard de Vinci. In: Ravaisson-Mollien, C. (Ed.) Transl. French by Institut de France, vol.3.

Del Viso J.R., Carmona J.R., Ruiz G., 2008. Shape and size effects on the compressive strength if high strength concrete. Cem Concr Res; 38:386.

Fairhurst J., Gillanders R., McMillan A., 1999. Building Stones of Edinburgh, Edinburgh Geological Society (2nd Ed.).

Fisher R.A., Tippett L.H.C., 1928. Limiting forms of the frequency distribution of the largest and smallest member of a sample. Proc Cambridge Philos Soc.; 24:180-90.

Galileo, Galilei Linceo, 1638. Discorsi e Demostrazioni Matematiche intorno a due Nuove Scienze, Elsevirii, Leiden. In: Weston, T. (Ed.) ;1730, English transl., pp178-81.

Hillerborg A., 1983.Concrete Fracture energy tests performed by 9 laboratories according to a draft RILEM recommendation: Report to RILEM TC50-FMC (Report TVBM;Vol.3015). Division of Building materials, LTH, Lund University.

Historic Environment Scotland, 2017: Advisory Standards of Conservation and Resilience for the Historic Building Environment in Scotland.

Hyslop E., McMillan A., Maxwell I., 2006. Stone in Scotland, UNESCO Publishing.

Kourkoulis S. K., Exadaktylos G. E., Vardoulakis I., 2002. The influence of notch geometry and non-linearity on the SIF in case of 3P-B marble specimens. In: Proceedings of 14th European Conference on Fracture, September 8-13, Krakow, Poland.

Kourkoulis S. K., Caroni C. and Ganniari-Papageorgiou E., 2005. A contribution to the size effect of natural building stones. In: Proc. Of the 5th GRACM Int Congress on Comp Mech, Limassol, Cyprus (Papadrakakis et al. Eds). Kantzilaris Publ, Nicosia, Cyprus: 495-502.

Kourkoulis S. K., Ganniari-Papageorgiou E., 2010. Experimental Study of the Size and Shape effects of Natural Building Stone, Construction and Building materials; 24(5), 803-810.

Kourkoulis S. K., 2011. An Experimental Study of the mechanical behavior of the 'Conchyliates' Shell-stone: Some irregularities of the Size Effects. Strain; 47; 344-356.

Leary E., 1983. The Building Limestones of the British Isles, Building Research Establishment Report, Department of the Environment, UK.

Malvar J., Warren G., 1988. Fracture Energy for Three-Point Bend Tests in Single-Edge Notched Beams. NCEL Technical Report, Naval Civil Engineering Laboratory, Port Hueneme, California.

RILEM Technical Committee 50-FMC, 1985. Draft Recommendation: Determination of the Fracture Energy of Mortar and Concrete by means of Three-Point Bend Tests on Notched Beams, Materials and Structures; 106, p. 285-290.

Rokugo K., Uchida Y., Katoh H, Koyanagi W.,1995. Fracture Mechanics Approach to Evaluation of Flexural Strength of Concrete. ACI Mat J;92.

Stewart M.R. 2016. Comparative Study of the Fracture Properties of Natural Building Stones used in Edinburgh. MEng Civil Engineering Honours Project, School of Engineering and the Built Environment, Edinburgh Napier University.

Vardoulakis I., Kourkoulis S.K., 1997. Mechanical Properties of Dionysos Marble. Final report of the Environment Project EV5V - CT93-0300, National Technical University of Athens, Greece.

Vardoulakis I., Kourkoulis S.K., Exadaktylos G.E., Rosakis A., 2002. Mechanical properties and compatibility of natural building stones of ancient monuments: Dionysos marble. In: Proc of the Intl W/shop: The Building Stone in Monuments, IGME Publishing, Athens: 187-210.

Vardoulakis I., Kaklis J., 2004. An experimental investigation of the size effect in indirect tensile test on Dionysos marble. In: Proc. of the 7th National Congress on Mechanics (Kounadis et al. Eds). Technical University of Crete Publishing, Chania, Greece:151-157.

Vayas I., Marinelli A., Kourkoulis S. K, Papanicolopulos S.A, 2009. Investigating the Fracture Behavior of Dionysos Marble: an experimental study. In: Protection of Historical Buildings, Vol. II, Mazzolani F.M. (Ed.), A. Balkema Book, Boca Raton, 1699-1704.

Walsh P.F., 1972. Fracture of plain concrete. Indian Concr J.; 46(11): 469-70, 476.

Weibull W., 1939. The phenomenon of rupture in solids. Proc R. Swed Inst Engng Res. (Ing Akad Handl Sweden); 153:1-55.