Fiber optic strain gages for stress analysis by means of the hole drilling technique

S. Sánchez-Beitia[1], I. Lombillo[2] & L. Villegas[2]
[1]*Faculty of Architecture, Basque Country University, Spain*
[2]*Department of Structural and Mechanical Engineering, University of Cantabria, Faculty of Civil Engineering, Spain*

Abstract

The article deals with the application of the hole drilling technique on structural elements of architectural heritage constructions by using eight fiber optic strain gages. The objective of the research is the on site deduction of the stress state on stone masonry of architectural heritage constructions. The hole drilling method is a Minor Destructive Testing (MDT) giving information about the Principal Stresses of the local stress state around the measured zone and, in consequence, it favours the estimation of the stresses associated with a certain direction, for example the vertical stress of a stone masonry element. Fiber optic technology allows the storage of the strains in the strain gages even when the unit of measure is temporarily not connected. Thus it will be able to monitor the stress measurements as a time function.

The tests carried out have compared the applied loads in a laboratory machine with the results obtained by the hole drilling technique through fiber optic strain gages. Until now only resistive strain gages have been used. In this sense the contribution is innovative with an evident advance towards the complete structural characterisation of stone masonry structural elements.

Keywords: hole drilling, stress measurements, cultural heritage, masonry

1 Introduction

The hole drilling technique has been widely applied in previous works to obtain the existent stresses in the structural elements in constructions of cultural heritage [1–5]. The method is based on the strains caught by resistive strain gages (RSG) glued over the element. These kinds of strain gages (made of

WIT Transactions on The Built Environment, Vol 112, © 2010 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM100451

copper) allows for only one experimental procedure. Once the measurement has finished is not possible to repeat the reading of strains in the strain gages. Fiber optics sensors can store the strains for successive readings, being able to generate a monitoring process. This is the reason why the authors try to analyze the results obtained by means of the hole drilling technique by using a set of fiber optics strain gages (FOSG).

2 Brief description of the hole drilling technique

The technique is based on the ASTM Standard E837-95 [6, 7] being applied to stone masonry since 1992. The restrictions of the technique are explained in this standard in detail. Three strain gages are sufficient for the deduction of a state of stresses in bi-dimensional situations. Nevertheless, usually eight strain gages are glued over a stone block in order to avoid experimental errors. The experimental procedure includes several steps with a transcendental influence for the final results. The surface is slightly polished in order to glue the strain gages over a smooth substrate. The strain gages are carefully glued over a circumference of diameter 4 cm with its centre identified as best as possible. The test begins recording the strains over 60 minutes at least before drilling. This aims at understanding the fluctuations around the zero strain. From previous experience the test is considered valid when these fluctuations do not exceed 5 μm/m. After the strains are stabilised, a hole of 3.2 cm depth with 3.6 cm diameter is drilled. The centre of the strain gages' position and the centre of the drill have to be as coincident as possible. The ultimate experimental step consists of recording the strains measured by the strain gages every 5 minutes over at least 120 minutes. According to the ASTM Standard E837-95 the strains ε_1, ε_2 and ε_3 measured by three strain gages "1", "2" and "3" (fig. 1) respectively are related with the stresses through the following expressions:

$$\sigma_{max} = \frac{\varepsilon_1 + \varepsilon_3}{A} - \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B} \tag{1}$$

$$\sigma_{min} = \frac{\varepsilon_1 + \varepsilon_3}{A} + \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B} \tag{2}$$

$$\beta = \frac{1}{2} arctan\left(\frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1}\right) \tag{3}$$

where ε_1, ε_2 and ε_3 are the strains recorded respectively at 0º, 225º and 90º with a direction of reference. σ_{max} and σ_{min} are the maximum and minimum principal stresses respectively and β the angle (measured clockwise) of σ_{max} with the direction of ε_1 (or σ_{min} with the direction of ε_3). From these values it is possible to deduce the vertical stresses (σ_{vert}).

The constants A and B are related to the Poisson Coefficient (ν), the Young Modulus (E) and two dimensionless parameters "a" and "b" that include the geometrical conditions of the test. Standard ASTM E837-95 establishes for "a" and "b" the values 0.2 and 0.5 respectively. Constants A and B can be deduced by means of the following expressions:

$$A = -4\left(\frac{1+\nu}{2E}\right)a$$
$$B = -4\left(\frac{1}{2E}\right)b \tag{4}$$

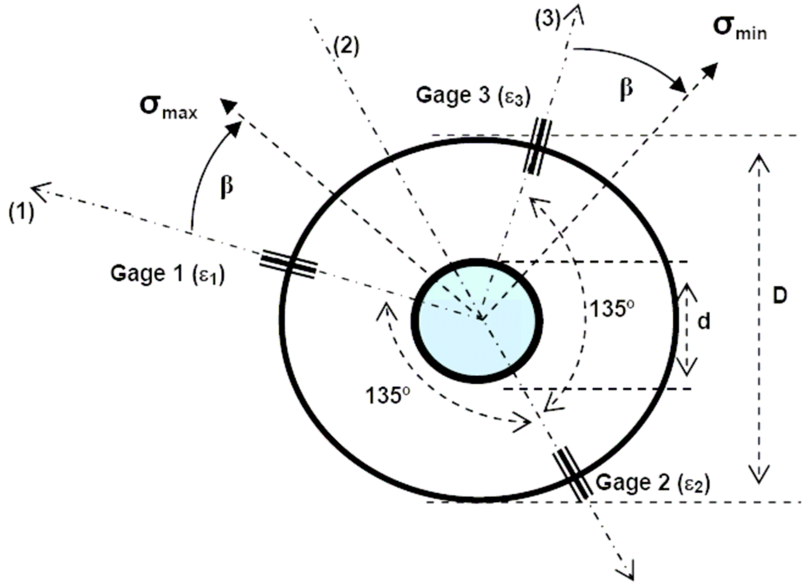

Figure 1: Layout of the geometry for the hole drilling technique. "D" is the diameter of the circumference of the strain gages whereas "d" is the diameter of the drill. The symbols (1), (2) and (3) show the directions of the strain gages 1, 2 and 3.

The value of Young Modulus (E) is obtained from specific tests on stone samples with a composition similar to the stone material used in the case studies. Alternatively this value is taken from library. The Poisson Coefficient (ν) is considered to be 0.25 in agreement with previous experience on sandstone [9].

The procedure above explained has been always applied in normal works by using RSG with a length of 6 mm.

3 Laboratory tests

The experimental works have been carried out over a stone block (35 cm x 35 cm x 31 cm). The hole drilling procedure has been performed in order to compare the stresses thus obtained with the applied load in a test machine at the laboratory. The results obtained by two kinds of strain gages have been compared after loading the stone block under a known load. The strain gages have been glued on two opposite sides. Eight RSGs have been placed on a side whereas eight FOSGs have been glued on the opposite side (figs. 2 and 3). Table 1 shows the load process over the sample and the strains recorded in a vertical strain gage of the two kind of material. The hole drilling procedure has

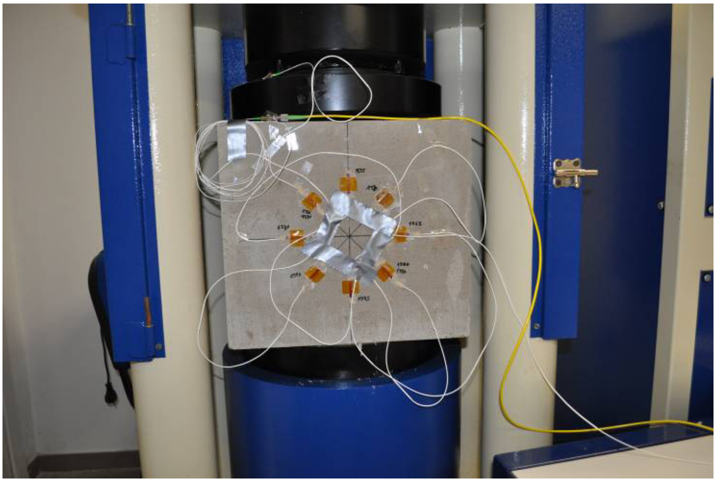

Figure 2: FPSG placed over a side of the sample.

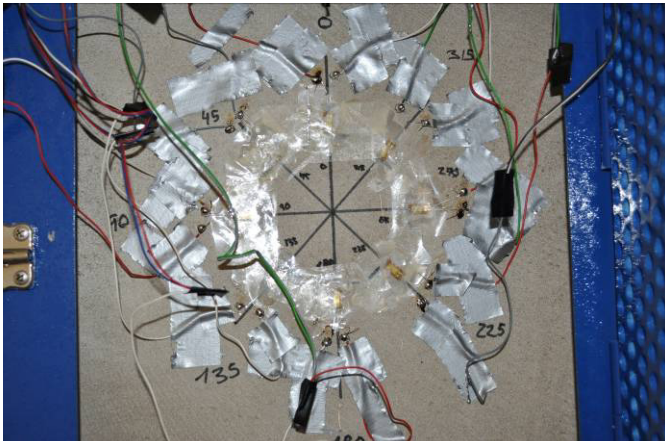

Figure 3: RSG placed over a side of the sample.

been performed on both sides at the final load (17 MPa). The experimental conditions for RSG follow the scheme mentioned above. The diameter of the FOSG circumference ("D" in fig. 1) has to be 14 mm due to both their size (15 mm length) and the requirements of the connection wires management. This new value for "D" affects the value of the constants "a" and "b". In this case ASTM E837-95 establishes for "a" and "b" the values 0.11 and 0.28 respectively.

The results here described have been obtained from strains recorded by the strain gages at 180º (vertical direction), at 90º (horizontal direction) and at 315º (figs. 2 and 3). The other five strain gages on each side have been saved for other experimental works in a different research field.

Table 1: Values of the applied loads and the strains recorded in vertical strain gages.

Applied stresses (MPa)	Strains in vertical RSG (microns/meter)	Strains in vertical FOSG (microns/meter)
0	0	0
4	46	22
8,06	146	260
12,11	256	450
17	390	700

4 Results

From library the value of Young Modulus (E) of the loaded rock (sandstone) has to be near 30000 MPa. The results shown in Table 1 allow an estimation of two values for Young Modulus of the sample depending of the strain gages classes. Selecting the last three steps of load process 36000 MPa is obtained for RSG and 18000 MPa for FOSG. Figs. 4 and 5 shows the strains recorded by using the

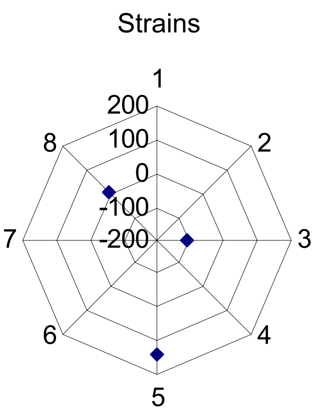

Figure 4: Strains recorded for the hole drilling technique by FOSG. The initial strains at 17 MPa relax after drilling.

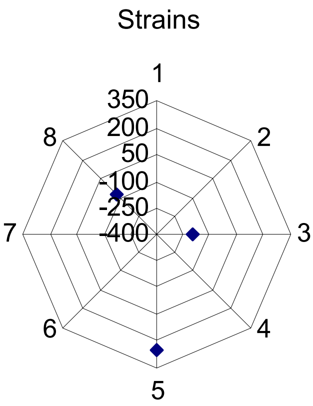

Figure 5: Strains recorded for the hole drilling technique by RSG. The initial strains at 17 MPa relax after drilling.

hole drilling technique on both sides, maintaining the sample loaded at 17 MPa. Table 2 shows the stresses obtained from these values. The strains for the hole drilling analysis are the differences between the initial strains (sample loaded) and the final strains after extracting material by drilling.

Table 2: Stresses deduced according the hole drilling technique for both kinds of strain gages. The sample is loaded under 17 MPa.

Strains for FOSG (microns/meter)		Strains for RSG (microns/meter)	
180º (E1)	138	180º (E1)	244
90º (E3)	- 113	90º (E3)	- 200
315º (E2)	0	315º (E2)	- 92
Vertical stress (MPa) for FOSG		Vertical stress (MPa) for RSG	
- 11		- 17	

5 Conclusions

The results obtained by using the two kinds of strain gages are absolutely different. The strains recorded by the two kinds of strain gages are different under same load (Table 1). The same conclusion can be deduced from the stresses obtained by means of the hole drilling technique (Table 2). RSG have been widely used in previous works having a great experience about their applications and limits. FOSG have been elaborated exclusively for this research. It is well known that the fiber optics sensors for strain or displacement measurements are widely proven. Nevertheless the obtained results for the FOSG are at the moment not considered like certain. The authors have not achieved to discover the reason for this trouble. Same result was detected in a similar work performed some months ago. It is foreseen the repetition of the tests with a careful control of the experimental parameters as detailed as possible.

References

[1] J. Barrallo, A. Zulueta, J. Caro, L Blanco, S. Sánchez-Beitia. Stress Measurements on Ancient Structures. *Experimental Techniques*, 19 (3), pp. 9-13, 1994.

[2] J. Barrallo, A. Zulueta, S. Sánchez-Beitia. The Donostia Method for the stress measurements in architectural heritage. *STRAIN*, 35 (3), pp. 107-112, 1999.

[3] S. Sánchez-Beitia. Stress analysís in the Altes Museum (Berlín) by means of the Hole Drilling Technique (Donostia Method). *Construction and Building Materials*, 21 (8), pp. 1680-1688, 2007.

[4] Santiago Sánchez Beitia. Stress analysis of the piers of the Tarazona Cathedral (Zaragoza-Spain) by means of the hole-drilling technique. *Construction and Buildings Materials*, 22 (5), pp. 966-971, 2008.

[5] Santiago Sánchez-Beitia, Luc Schueremans, Koenraad Van Balen. In site stress measurement on the piers of the Saint Jacobs church in Leuven (Belgium). *International Journal in Architectural Heritage*, 3 (2), pp. 110-125, 2008.

[6] Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method. ASTM 837-95 Standard. American Society for Testing Materials.

[7] Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method. ASTM 837-01 Standard. American Society for Testing Materials.