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Fatigue performance of a connection for GRC cladding panels

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ABSTRACT

The façade or building envelope is one of the most demanding structural parts of a building, both in terms of durability and structural performance. Among the several different materials suitable for external cladding, glass reinforced concrete (GRC) panels, have recently gained popularity among architects, engineers and contractors in the last years. The high tensile strength, durability as well as the great variety of shapes, sizes and colours make GRC as a particularly suitable choice for thin, light, free-form cladding façade elements.

The general behaviour of GRC is well known but there are still some areas on which there is limited or no research. One such example is the connection of the panels to the supporting structure where stress concentrations are generated and that could activate different failure modes. Furthermore when used as façade element there are several different actions such as wind, snow as well as thermal expansion and earthquake which excite cyclically the GRC panel over its service life. The consequent fluctuation of the stress concentrations raises the need for a fatigue-based design, which is outside the scope of mainstream design guidelines and standards.

In this presentation results of a series of fatigue tests on a GRC to metal anchorage will be presented and discussed based on a real case study. The analysis of the wind load as cyclic load and the definition of the corresponding stress levels and number of cycles for the fatigue test will be also discussed.

INTRODUCTION

Façade panels are subjected to variations of the applied loads during their service life. Wind load, seismic load but also thermal expansion fluctuate over the life time of the façade. These repeated loadings may induce micro-cracks to grow progressively up to change the material’s mechanical properties [1]. This process of structural degradation is called fatigue.

When the stresses generated by the fluctuating loads are significant, there is a need for fatigue design, especially when new materials or systems are implemented. Glass Reinforced Concrete (GRC) even though was invented many years ago is not as widely used as some other construction materials such as concrete or steel. This is partially related to the lack of experimental investigation of its long term performance.

The available literature on fatigue of GRC provide conflicting views. For some authors, the fibres in the GRC, when compared with plain concrete, do improve the fatigue behaviour significantly under low loading frequencies (up to approximately 10^4 cycles) [2, 3]. Some experiments have shown how the presence of fibres in the matrix contribute towards arresting sudden crack formation by bridging cracks, and thus inhibiting the crack extension under cyclic loads [4]. Other authors, instead, consider the presence of fibres and particles as weak regions in the material where fatigue cracks can nucleate [5].

Focusing on the façade panels, one of the most critical areas sensitive to fatigue is the connection to the supporting structure where unavoidable stresses concentration occurs. These stress under cyclic loading can initiate cracks and bring the panel system to failure [6]. Therefore, the effects of repeated loadings should be considered and, if significant, taken into account in the design. This approach is further highlighted in [7] which suggests to consider low-cycle fatigue in the design of the anchor for wind load and other cyclic movements.

In this paper the connection between a GRC panel rib and a steel bracket, kept together by a mechanically fixed cast-in bolt, has been part of a fatigue study. The connection is part of a real world project application, the Grand Theatre de Rabat (see Fig 1). For this project GRC cladding elements have been chosen as the most suitable solution to fulfil the complex geometry of the envelope. There are approximately 5000 GRC panels on the façade which are connected to the supporting structure through more than 17000 adjustable bracket systems (see Fig 2). This connection system has been developed by the building engineering consultant Newtecnic ltd.

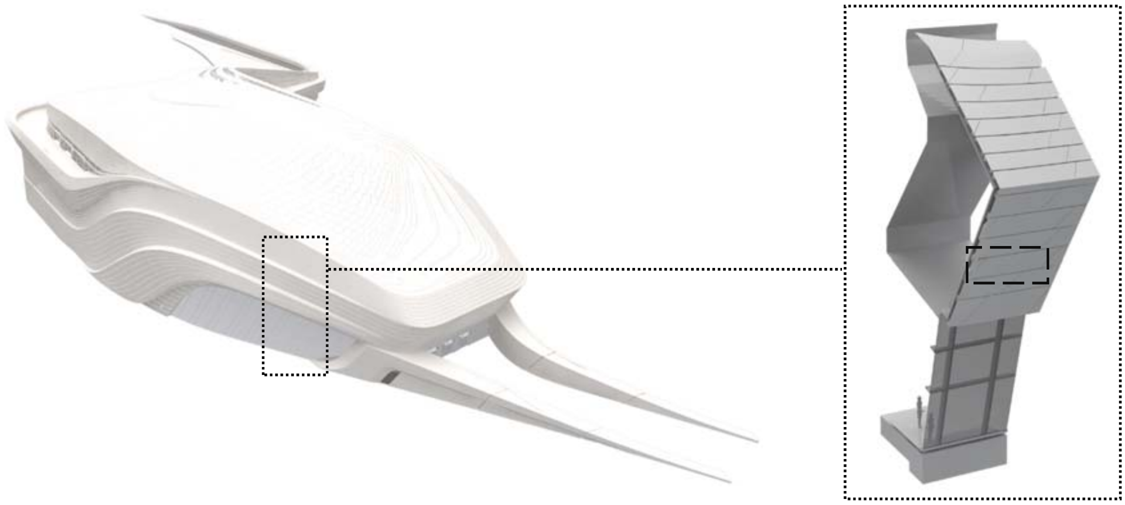

Figure 1: Assonometric view of the whole building (left) and typical bay (right)

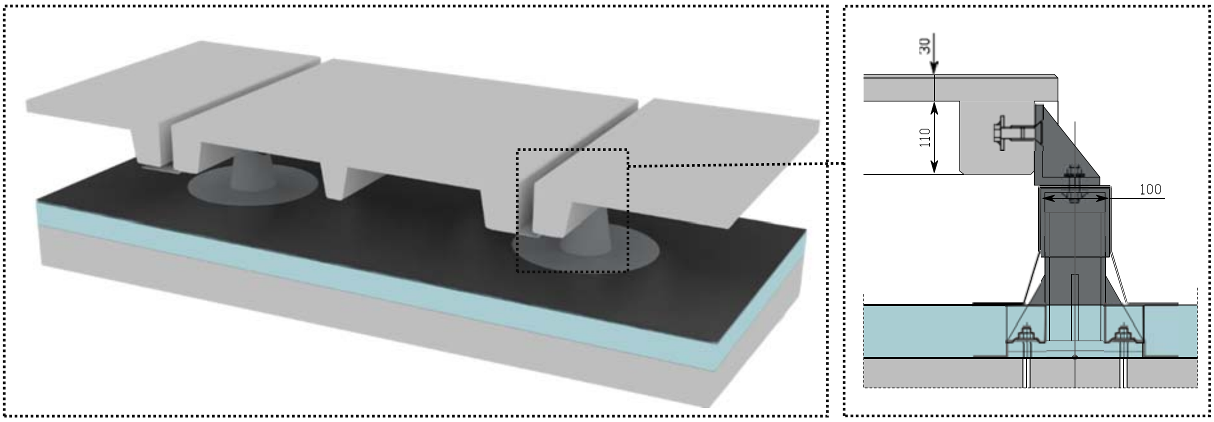

Figure 2: 3D view of the panel system (left); 2D view of the bracket (right)

To the authors' knowledge, up to date there is no standard procedure for carrying out fatigue tests on GRC. Therefore fatigue tests have been carried out to provide data concerning (i) the assessment of the design fatigue strength of the connection subjected to real world loads and (ii) validation of numerical and analytical models of the connection.

PARAMETERS OF THE FATIGUE TEST

Geometry of the Specimen

In this study the assumed specimen size is 600×110×150mm, which represents the edge rib of the GRC panel (see Fig 2(right)). The sample includes the top part of the metal bracket used to connect the panel to the supporting structure. The sample is pinned at the two ends, using two steel rods at bottom and top surfaces, and subjected to a point load applied to the bracket. The current setup, and in particular the 450mm span, was chosen able to reproduce the same stress distribution, around the connection, as in the real on-site loading conditions (see Fig 3). A finite element model of the two configuration was developed and used to compare the stress distributions.

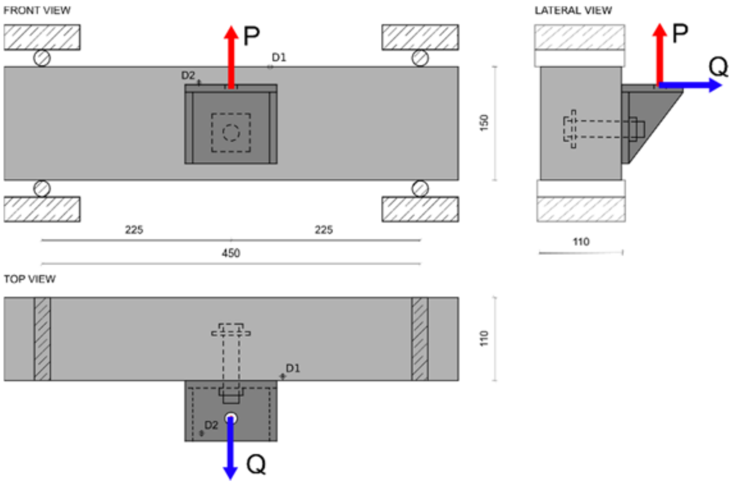

Figure 3. Front,Top and Lateral views of the specimen with transversal (P) and axial (Q) load (Dimensions are in mm). D1 and D2 represent two different positions where displacements have been recorded during static and fatigue test.

Fatigue Load Amplitude

The GRC panels in this study have several possible orientations in the real world structure. As a consequence the forces applied on the structure are combinations of permanent load and wind load. Both these forces are assumed equally distributed among the four supporting brackets. The fluctuating wind is applied in the transverse/shear direction (force P in Fig. 3) while in the axial direction (force Q in Fig 3) there is a negligible oscillation, of the applied loads (self-weight, thermal expansion). Therefore only the fatigue performance along the transverse direction (force P) has been investigated.
For the biggest panel, the permanent load (G) on the bracket due to the horizontal/inclined panel self-weight is about 6.0kN; while wind pressure/suction (W) acts as a uniform pressure perpendicular to the panel surface and generates a transverse force of ±4.0kN at the connections. The maximum load applied to the bracket (S_{max}) is the sum of G and W, i.e. $S_{max} = G + W = 10kN$; while the minimum load is $S_{min} = G - W = 2kN$. These values define the fatigue load ratio ($R = S_{min}/S_{max}$) of this fatigue test being R=0.2. Table 1 summarises the fatigue parameters including the mean load ($S_{mean} = G$) and load amplitude ($\Delta S = W_{max} - W_{min}$). Figure 4 gives a visual representation of the load cycles. Under this conditions the bracket transversal load is always positive with no reverse cycles.

Table 1. Fatigue Design Load tests

	S_{mean}	ΔS	S_{min}	S_{max}	$R = S_{min}/S_{max}$
	[kN]	[kN]	[kN]	[kN]	[-]
Load Case A	6.0	8.0	2.0	10.0	0.2

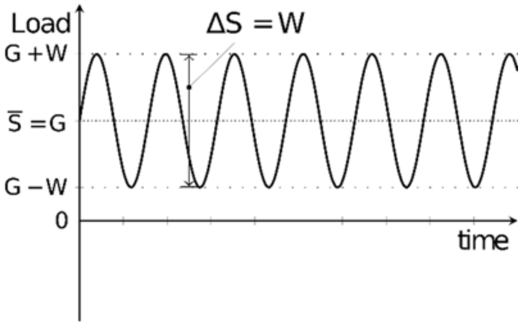

Figure 4. Load Cycles: Permanent Load and Wind Load (G + W)

Frequency of the test

Differently than loads with one or few frequencies, wind has a random nature. Therefore it operates at a wide range of frequencies which might match with the frequency of the structure. As consequence an amplification of the load might occur. The resonance problem was then investigate through spectral analysis. The power spectral density function for the wind load was compared with the modal frequencies of the panel. A numerical modal analysis of the biggest GRC panel including the four metal brackets was performed. Fig 5(right) shows the modal shape of the first modal shape (frequency of 12.7Hz).

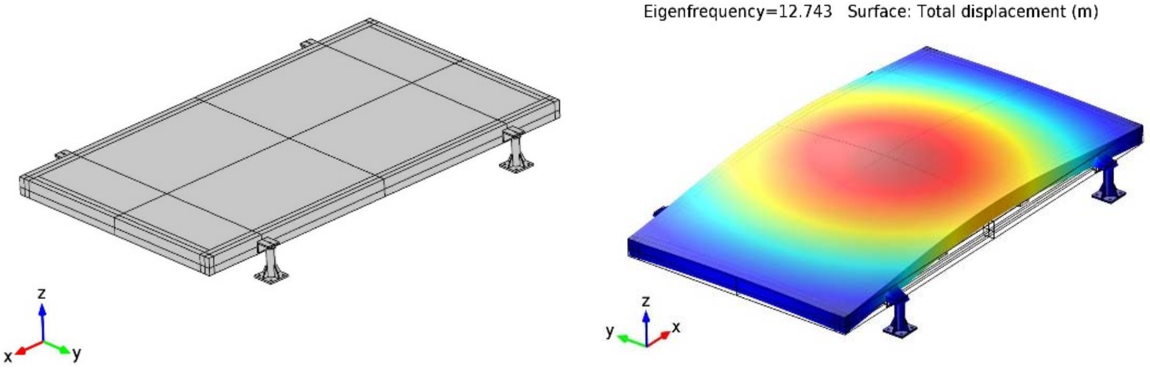

Figure 5. FE model for the frequency analysis (left); First mode shape of the assembly (panel and bracket) (right)

In this case at the lowest panel frequency the amplitude of a generic wind signal was lower than 5% of the design load and it did not represent a risk of resonance. With no resonance problem, the fatigue loads do not have to be amplified and the frequency chosen for the fatigue test can be the maximum possible frequency of the testing equipment, i.e. 5Hz.

Test Procedure

In this study the fatigue strength was investigated through the application of load cycles (S_{mean}, ΔS) on a pinned-pinned specimen. During the test the number of cycles and the displacement at mid-span were recorded. The loads were applied until failure of the specimen or up to 2million cycles. If the second case, the specimen was also tested up to failure under low speed rump load and the resulting strength compared with the failure load of similar specimens tested before any fatigue cycles.

INSTRUMENTATION AND SET-UP

During all the tests the vertical displacement of two points of the metal bracket have been recorded using a linear potentiometer displacement transducer (Fig 6(left)) and a laser displacement transducer (Fig 6(right)) respectively. A TC4-AMP load cell with maximum load capacity of 50kN was used to measure the applied force. The load was applied using a hydraulic actuator controlled by a two axis portable stand-alone controller, able to generate different types of automated actuator motion. In particular the unit is able to apply loads up to 30kN at variable frequencies and to record signal with sampling rates up to 2kHz. Figures 7(left) and (right) show an overview of the equipment and a close view of the controller.

Figure 6. Linear potentiometer displacement transducer (left) and Detail of the laser displacement transducer (right)

Figure 7. Overview of the Fatigue Test Equipment

The specimens were tested for 2 million cycles with a sinusoidal load ranging between +2kN and +10kN (fatigue stress ratio *R* = 0.2). The maximum frequency for this load range and the available equipment was 5Hz. The total duration of the test was 112 hours. Regular visual inspection every 100 thousand cycles were conducted during the test.

TEST RESULTS

For the load case A (R=0.2), the specimen did not fail after the 2 million cycles, and no visible damage was found in the GRC or in the metal parts. The inspections during the test did not show any relevant loosening of the bolt or local crushing of the GRC.

Static Test after Fatigue

The sample did not fail after 2 million fatigue cycles and therefore it was tested up to failure under short duration rump loading. The results were then compared against the shear-out static strength of similar specimens tested before any fatigue cycles. The comparison shows no relevant change of the shear-out capacity of the system. Only a very small reduction (<2%) of the shear-out strength from 33.8kN down to 32.18kN was observed. For both cases Fig. 8 shows a linear behaviour of the system up 15 kN which correspond to the Limit of Proportionality (LOP) of the material. As the aim of the test was to look at the strength of the connection no particular attention was given to the position of the displacement transducer, being on D1 of Figure 3 and on D2 for the fatigue test. As consequence the difference in stiffness between the two curves of figure 8 cannot be considered as a consequence of the fatigue test.

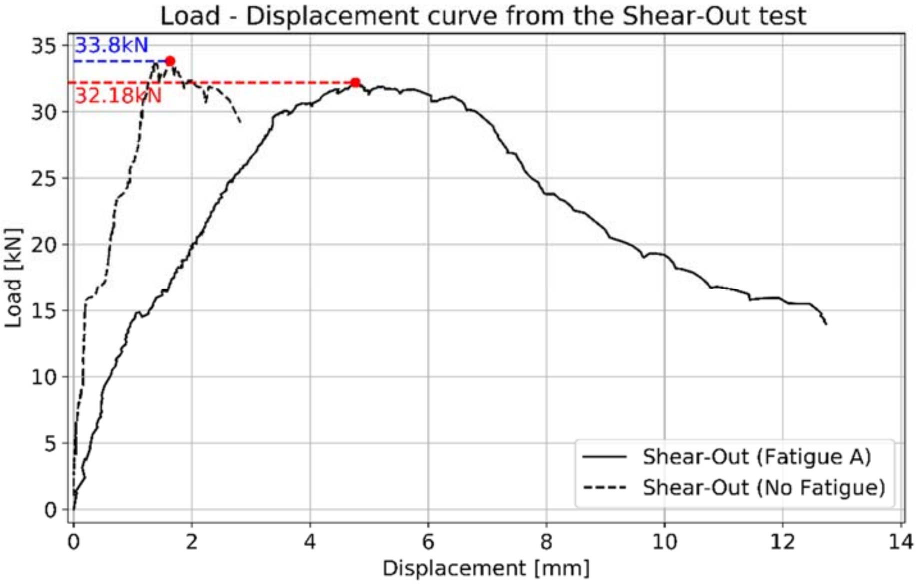

Figure 8. Shear-Out Load - Displacement curve of the GRC beam with metal bracket after 2 million Load Case A

CONCLUSION

Experimental investigations of fatigue strength of a connection for GRC façade systems has been part of a preliminary study. The fatigue test was performed on a series of samples and for a specific stress ratio $R = 0.2$. For this load case, which represents the maximum design load with a return period of 50 years, the specimens did not fail after 2 million cycles. In particular, the fatigue cycles did not have a relevant effect on the strength of the GRC connection.

However it must be remembered that only few specimens were tested and therefore the outputs of this research can be taken only as an initial estimation of the real strength of the connection.

The results allowed to gain a first understanding of the long term behaviour of a bespoke connection between a metal bracket and GRC, providing an estimation of its shear-out strength.

Table 2 summarises the final outcomes of the fatigue test listing both shear-out strengths before and after fatigue cycles.

Table 2: Summary results of Fatigue shear-out test of the GRC beam with the metal bracket under load Case A

	Static Strength [*kN*]	Static strength after Fatigue [*kN*]
Static Shear-out	33.8	33.18

A series of future test on a wide number of specimens will allow to provide statistically stronger results.

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