THE THERMOELASTIC TECHNIQUES FOR THE MEASUREMENT OF STRESSES DISTRIBUTION ON COMPONENT OF STRUCTURES OR MACHINES

Roberto Marsili
Università degli Studi di Perugia
misure@unipg.it

Gianluca Rossi
Università degli Studi di Perugia
gianluca@unipg.it

Abstract. *Because of the continuous evolution of the market in terms of quality and performance, the mechanical production industry is subjected to more and more pressing technological challenges. In this frame the use of advanced measurement technique as the thermoelasticity, allows the engineers to have a fast and reliable tool of experimental investigation, optimization and validation of the FEM models of those critical parts as for example parts of car frames. In this work it is shown how the thermoelastic measurement technique can be used to optimize mechanical components, as method of experimental investigation and as technique of validation of numerical models.*
The measurement technique developed for this purpose is described together with the calibration method used in the test benches normally used for fatigue testing and qualification of these mechanical components. The results obtained show a very good deal with FEM models and also the possibility to experimentally identify the concentration levels of stress in critical parts with a very high spatial resolution and testing the effective geometry and structure material.

Keywords*: measurement of stress pattern, thermoelastic stress analysis, car frames analysis, stress pattern on differential gears, FEM model validation.*

1. Introduction

The design and development of a new component of structures or machines, when reliability, safety or costs due to component failure are relevant normally requires both an experimental and a theoretical approach (Tomlinson John R. Yates, 2001). For the second finite element models (FEM) are of common use, both for static and dynamic loading conditions (Ju S.H. Lesniak and J.R. Sandor, 1997).

Experimental validation of FEM models is normally performed by strain gauge for the deformation measurements on the component prototype or on a model of it, under operating conditions or standard loadings in laboratory test benches. Strain gauges, anyway, allow only measuring stresses in few points of the component and have a limitation in spatial resolution due to sensor grid dimensions. To overcome these limitations other non contact and full field techniques have been developed: photoelasticity, for example that requires a model of the components made of a particular material or photoelastic coatings on the components surface. Other no contact full field techniques, able to measure dynamic component deformations but only in dynamic conditions, are based on laser scanning vibrometers. Also another optical technique, like holography, Moiré and speckle, for example, has been used for this purpose.

In this paper thermoelasticity is considered and tested in order to have an experimental experience about its possibilities for FEM models validation of mechanical components.

Two applicative examples are illustrated in order to demonstrate the validity of this technique: the measurement of stress pattern on high performance car frames and the measurement of stress pattern on differential gears.

In all the activities we have designed and realized test benches able to load the components as similar as possible to their working conditions.

2. Thermoelastic's theory

The phenomenon of material changing temperature when it is stretched was first noted by Ghough in 1805 who performed some simple experiments using strand of rubber, but the first observation in metals of what is now known as the thermoelastic effect was made by Weber in 1830: he noted that a sudden change in tension applied to a vibrating wire did not cause the fundamental frequency of the wire to change as suddenly as he expected, but the change took place in a more gradual fashion (Rocca R., and Bever M. B., 1950). He reasoned that this transitory effect was due to a temporary change in temperature of the wire as the higher stress was applied. In 1974, the Admiralty Research Establishment approached Sira Ltd to determine relationship between stress and the temperature changes that may be produced by an applied load. Sira confirmed feasibility and over the next four years, with fundings from English Ministry of Defence, developed a laboratory prototype called Spate (Stress Pattern Analysis by measurement of Thermal Emissions) for an application research.

The scientific development of the thermoelastic effect, which is well known on gases, where a temperature variation gives a pressure variation, has been known in solid materials for short time because of the small variation of induced temperature (in the steel where the stress level is near the yield point, the temperature increases of 0.2°C). The thermoelastic technique for the measurement of stress distribution has been developed as soon as they have discovered a new temperature measurement technique, based on the emission of infrared radiation, with high sensibility.

The system consists on a differential thermocamera and on a software for the post processing of the image. The thermocamera measures the small temperature variation in the mechanical component induced by a dynamic applied load. Thanks to the software it is possible to have the map of stress distribution on the surface of the structure. The resolutions (supplied from the thermoelastic measurement systems) depend on the material characteristics; they are typically 1 MPa for the steel and 0.4 MPa for the aluminium (John R. Lesniak, Bradley R. Boyce, 2001; N. Harwood, W. M. Cummings, A. K. McKenzie, 2002; Harwood N., Cummings W.M., 1991).

The structure must dynamically be loaded with frequencies high enough that the thermodynamic conditions in the material can be considered adiabatic (Offermann S., Beaudoin J.L., Bissieux C., Frick H., 1997). Under these hypotheses it is possible to have a relationship between the mechanical energy and the thermal energy of the structure. The minimum frequency of the applied load depends on the thermal characteristics of the material and on the gradient of the stress fields. The relationship to determine the sum of the principal stress $\Delta\sigma$ thanks to the thermoelastic principle is:

$$\Delta\sigma = -\frac{D \times R \times \rho \times C_P}{\alpha \times T \times \zeta} \times V \qquad (1)$$

D is the calibration factor, R is a correction factor which compensates for temperature-dependent changes in radiation intensity and wavelength, ρ is the material density, C_p is the specific heat at constant pressure, α is the coefficient of thermal expansion, T is the temperature, ζ is the surface emissivity, and V is the RMS of the signal measured by the infrared sensor. By the thermoelastic technique it is possible to measure the map of stress distribution also in complex geometries. Normally it is necessary to paint the surface of the mechanical component to increase and make the emissivity uniform. This no contact technique can have a high spatial resolution, which depends on optical lenses of the thermocamera.

In order to obtain the Stress distribution in terms of quantities values, a calibration process is required.

This last can be realized by using a common strain gauge, placed in a zone where the stress gradient is the smallest possible.

In this case the calibration factor K is calculated using the following equation (Stanley P. and Chan W. K., 1986):

$$K = \frac{E \cdot (\varepsilon_x + \varepsilon_y)}{S_{Avg.}(1-\nu)} \qquad (2)$$

E = Young's Module

ε_x, ε_y = Principal strain

$S_{Avg.}$ = A/D mean value

ν = Poisson's Module

Generally in order to perform the calibration, a double axis strain gauge is used, with the aim to acquire the sum of the two principal strains (Huang Y.M., Abdel Mohsen H.H., Rowlands R.E., 1990).

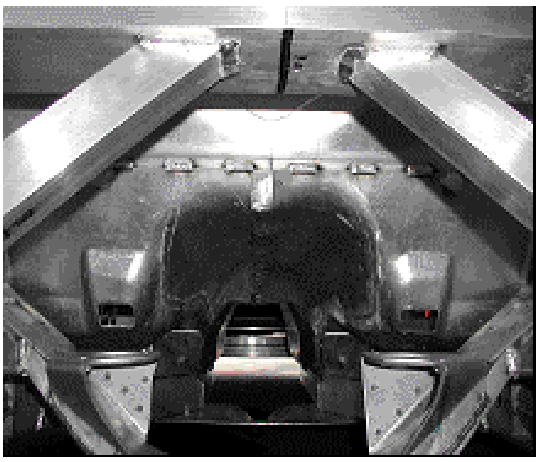


Figure 1. Car frame in analysis

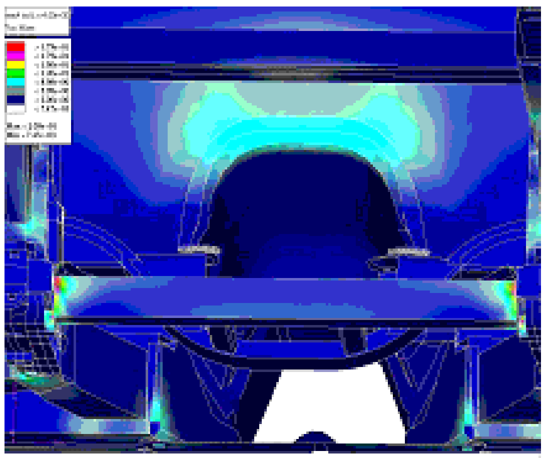


Figure 2. FEM analysis results

3. High performance car frames analysis

In this activity we have analysed the mechanical behaviour of some components of a high performance auto frames, we have found somehow critical in the experimental work tests. The Figure 1 shows the photo of the frame in study.

The Figure 2 shows the FEM model developed. The presence of notches, of welding and of bracing causes strains concentrations, as highlighted in the numerical analysis.

On these more stressed points, the employment of the classical measurement techniques based on strain gauge is very difficult because of the not planarity of the surface, the insufficient superficial finish and the small dimensions. The employment of the thermoelasticity, a measurement technique without contact for the distribution solicitations, gives us very important information.

The test bench, equipped with the hydraulic shaker, generates a cyclical load on the frame which has been painted through a dull black paint, in order to uniform the thermal emissivity of the body.

An electrical strain gauge has been pasted on the frame to scale the thermographic frame in stress frame, as well as to generate the reference signal necessary to the TSA system, to synchronize the frame grabber with the dynamic cycle load (Harish G., Szolwinski M. P., Farris T. N., Sakagami T., 2000).

In fact the Delta Therm 1550 use the Lock-in amplifer technique to acquire only the temperature change synchronous with the applied load.

At the same time it allows us to improve the signal-noise ratio. The Figure 3 presents a typical result that can be

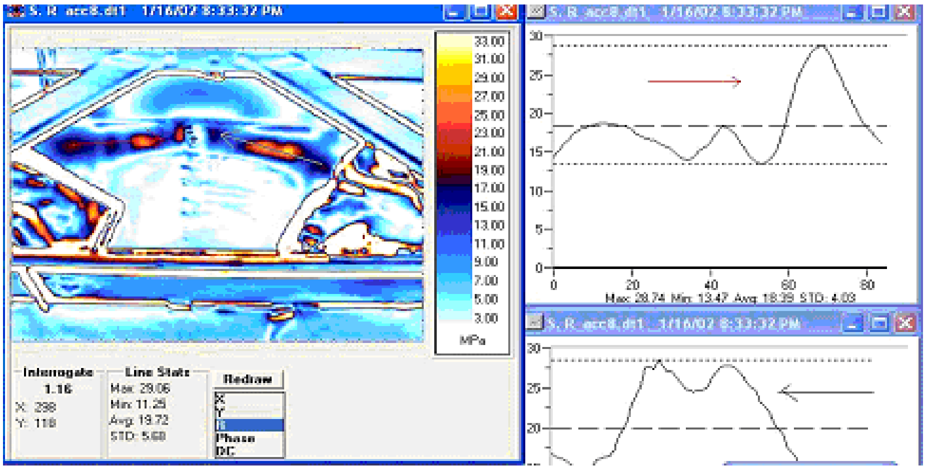


Figure 3. Typical thermoelastic results

obtained using this type of measurement technique. In the same picture it is also possible to determine the stress concentrations, near the constraint section and the zones where the shut is present. The thermoelastic stress map has been scaled by means of a correction factor, calculated with the equation (2), using the strain gauge. In this way, through the equation (1) a differential thermographic frame becomes a stress distribution map.

The previous TSA image is very useful to validate the FEM distributions in terms of sum of principal stresses. In this case the great correlation between FEM analysis and experimental results appears clearly. Drawing an interrogation line as shown in Fig. 3, it is possible to evaluate the stress trend along the same line as reported to the right of the same Fig. 3.

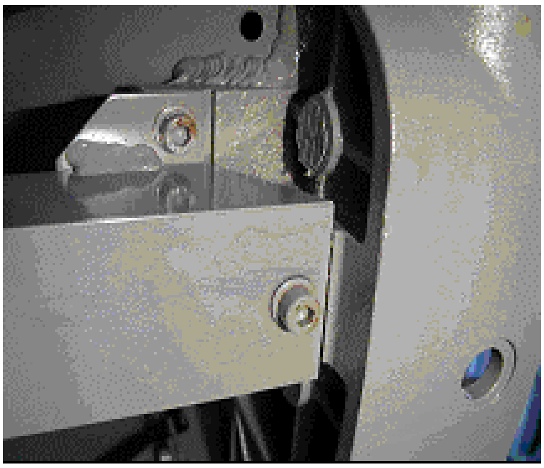


Figure 4. A car bracing analisys

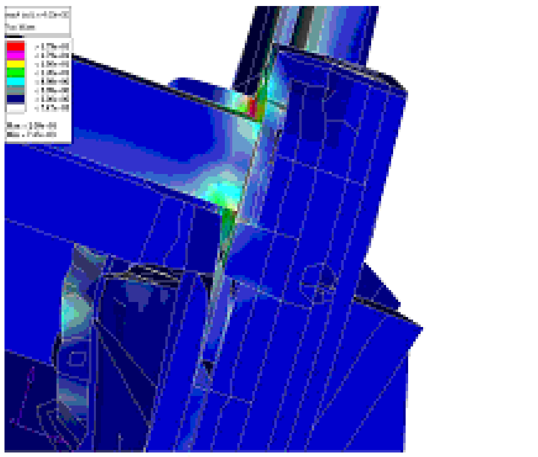


Figure 5. Typical FEM result

The qualitative and quantitative coincidence of the experimental and numerical results now allows us to use the model to change the geometry and the sections of the frame, or to insert a bracing, in order to reduce at the maximum the concentration of strains, without repeating the experimental tests, with economic and time advantages.

The Figure 4 shows an example of a bracing welded on the frame. By the numerical analysis it is possible to see the strains concentration in correspondence of the bracing, which could cause fatigue break of the component.

The same strains concentration is also seen in the experimental analyses by Thermoelastic system (Fig. 6). The thermoelastic experimental analysis highlights an elevated concentration of strains also around the screw, not predicted, instead, by the FEM analysis.

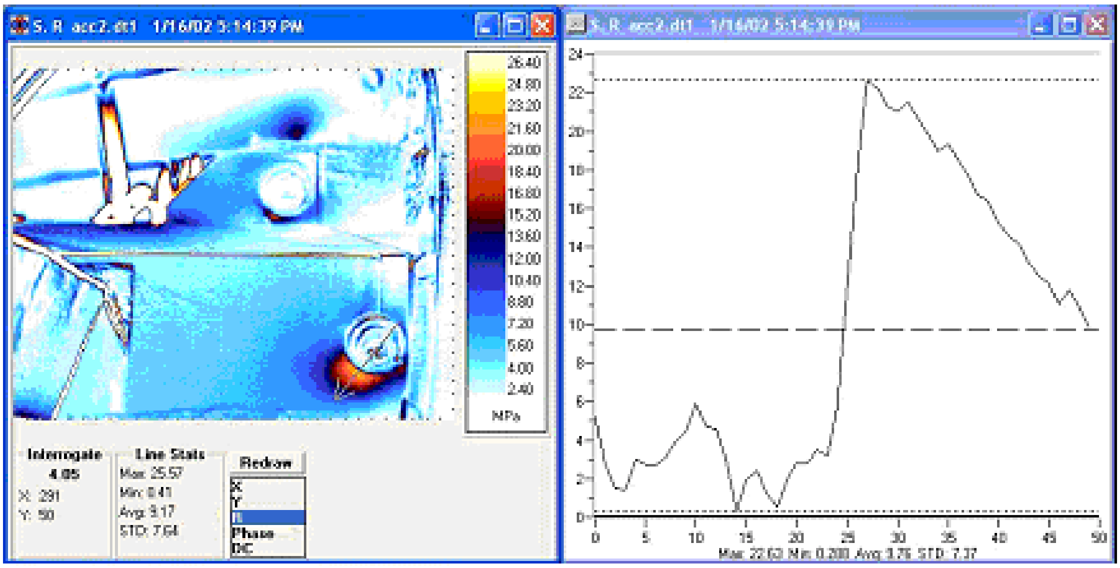


Figure 6. Thermoelastc stress analysis

4. Measurement of stress pattern on differential gears

A subsequent example of application of the thermoelastic technique is the measurement of stress on differential gears. The preliminary activity is the development of a suitable test bench able to load the component as much as possible similar to its working conditions; we tried to obtain an adjustable cyclical torque, in magnitude between 0 and 800 Nm and in frequency between 0 and 10 Hz. This was obtained by a beam welded to the pinion of the differential gear and loaded with a pneumatic system (Fig. 7); in this way it is possible to change the torque by changing the connection point and the piston stroke, while increasing or decreasing the air pressure makes the change of the loading frequency possible. The load amplitude control is realized by using a high precision load cell, whose output signal is also used as reference signal to synchronize the thermographic acquisition with the surface's thermal change due to the external load.

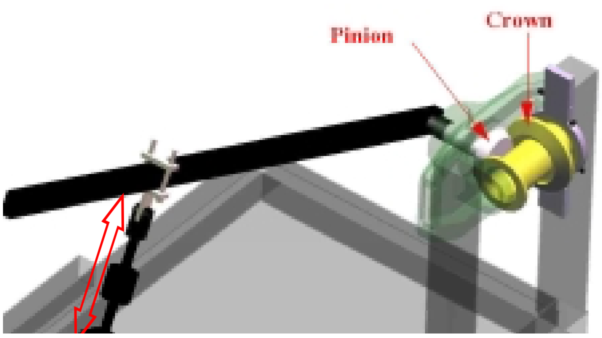


Figure 7. Test bench for the load application in the differential gear pinion

Figure 8. Particular of the investigated zone

In Figure 8 the area of interest for stress measurement is shown.

In order to obtain an optical access to tooth contact area, it was necessary to realize a particular differential gearbox casting by removing material without significant changing torsional stiffness of the external box.

The differential gear here analysed normally works with a typical torque value of 800 Nm. To simplify the problem, the distance between pinion and piston was fixed to 1 meter, in this way the only variable parameter is the piston stroke. In this configuration it is possible to individually adjust the torque magnitude by changing piston stroke and the load frequency by changing the air pressure. In fact changing the piston stroke means to change the beam deformation therefore the torsion applied to the pinion.

The Figure 9 shows a typical measurement example. The arrow denotes a critical stress concentration around the edges hole.

The test was performed in order to a have a comparison between two different geometries; in the first type, illustrated in Fig. 10, the connection hole is bigger and the stress levels are higher than in the second differential gear type, illustrated in Fig. 11. The maximum values measured were respectively 120 MP as in the first type and 50 MP as in the second. The modified geometry allows a reduction of the 60% of the peak value.

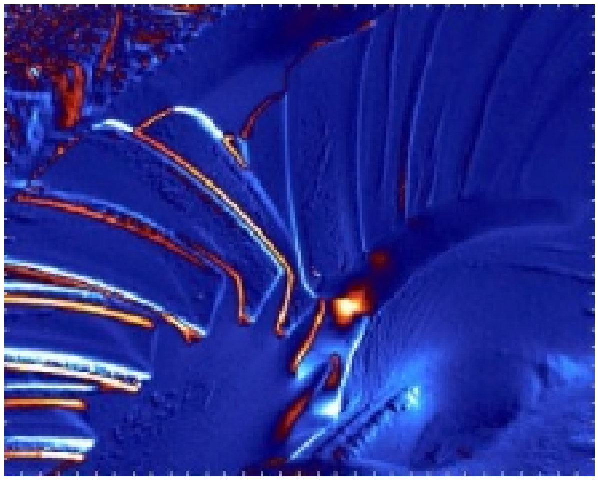
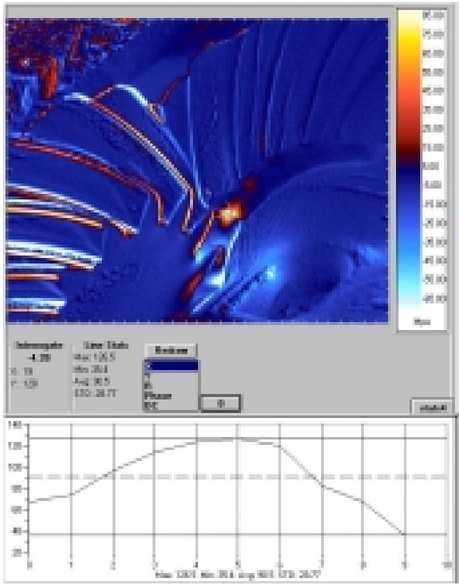


Figure 9. Typical stress pattern measurement on differential gears.



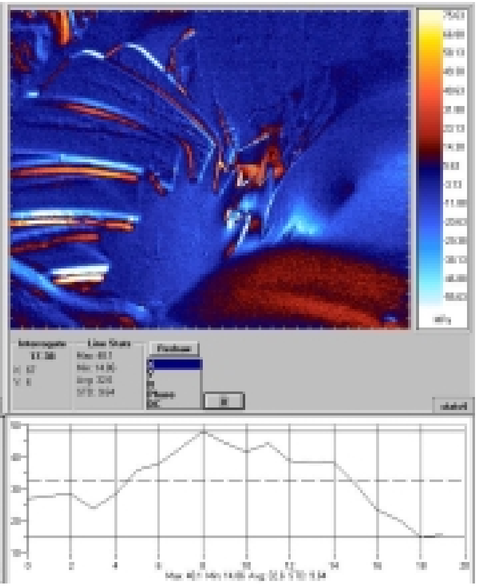


Figure 10. Differential gear Type 1

Figure 11. Differential gear Type 2

5. Analysis of the typical uncertainty

Normally in the thermoelastic measures the calibration comes from the measurement of the deformation by a strain gauge rosette in a point of the structure. To put on the strain gauge rosette we have considered certain points with a high and regularly distribuited solicitation. Repeated measurements by stain gauge of the principal strains and the relative measure of the infrared intensity radiation, allow estimating the calibration factor K, varying the applied load, the observation area and the excitation frequency. The best available estimate of the thermoelastic constant $\bar{k}$ expected value is $\bar{k}$ = 0,14 MPa/mV. The experimental standard deviation is $s(\bar{k}) = 0.01$ MPa/mV.
The composed uncertainty on the value of the thermoelastic constant K can be determined basing on relationship (1) as follows (3):

$$\partial K = \left|\frac{\partial K(E)}{\partial E}\partial E\right| + \left|\frac{\partial K(\varepsilon_x)}{\partial \varepsilon_x}\partial \varepsilon_x\right| + \left|\frac{\partial K(\varepsilon_y)}{\partial \varepsilon_y}\partial \varepsilon_y\right| + \left|\frac{\partial K(V)}{\partial V}\partial V\right| + \left|\frac{\partial K(\nu)}{\partial \nu}\partial \nu\right| \quad (3)$$

Assuming a relative uncertainty of 2% on the Poisson and Young modulus of the materials, of 2% on the determination of the principal strain ε and 2% on the RMS of the signal measured by the infrared sensor *V*, the combined standard uncertainty is $\partial K = 0.009$, and so relative typical uncertainty is

$$\frac{\partial K}{K} = 9\% \tag{4}$$

6. Conclusions

In this work some possible applications of thermoelastic measurement technique have been presented for the stress maps measurement in the mechanical components. When a test bench has been developed, in order to load the component in testing, it is possible, in a few minutes, to measure the principal components of superficial tension, with an elevated spatial resolution and an uncertainty measurement lower than the 9%. Two typical examples of application have been shown in order to demonstrate the potentialities of this technique: the measurement of stress pattern on high performance car frames and on differential gears for agricultural machinery. In both cases, the results obtained confirm the numerical analyses, highlighting critical points also not immediately recognizable with the FEM analysis.

7. References

John R. Lesniak, Bradley R. Boyce, 2001, "A High-Speed Differential Thermographic Camera", Stress Photonics Inc. 565 Science Drive Madison, WI 53711

N. Harwood, W. M. Cummings, A. K. McKenzie, 2002, "An introduction to Thermoelastic Stress Analysis"

Tomlinson John, R. Yates, 2001, "An investigation of crack closure using thermoelasticity", Rachel A. University of Sheffield UK.

Harwood N., Cummings W.M., 1991, "Thermoelastic Stress Analysis" Adam Hilger.

Harish G., Szolwinski M. P., Farris T. N., Sakagami T., 2000, "Evaluation of fretting stress through full-field temperature measurement" ASTM STP.

Huang Y.M., Abdel Mohsen H.H., Rowlands R.E., 1990, "Determination of Individual Stresses Thermoelastically", Experimental Mechanics, Vol. 30 (1), pp. 88-94.

Ju S.H. Lesniak, J.R. Sandor, 1997, "Numerical simulation of stress intensity factors via the thermoelastic technique", Experimental Mechanics, vol. 37 (No. 3), pp.278-284.

Offermann S., Beaudoin J.L., Bissieux C., Frick H., 1997, "Thermoelastic Stress Analysis Under Non-adiabatic Conditions", Experimental Mechanics, Vol. 37 (4), pp. 409-413.

Rocca R., Bever M. B., 1950, "The Thermoelastic Effect in Iron and Nickel (As a Function of Temperature)", *Trans. AIME*, vol. 188, pp. 327-333.

Stanley P., Chan W. K., 1986, " The determination of stress intensity factors and crack tip velocities from thermoelastic infra-red emissions", Proc. of International conference of fatigue of engineering materials and structures, c262, IMechE, Sheffield, UK, pp. 105-114.