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Applicability of X-Ray Diffraction Technique for Stresses Quantification in Metallic Structural Elements

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Abstract Since 2009 the research group managed by the authors promotes the applicability of X-Ray Diffraction technique (NDT) for global stresses measurements in metallic structures for civil engineering and building. There exists standard portable equipments in the market for different applications of those here shown (residual stresses measurements). This paper shows some tests prior the complete calibration for any situation in such a way that can be applied to the quantification of stresses in service. Until now a metallic bar at the Oporto Cathedral, two corrugate bars at laboratory and a small metallic structure at laboratory have been tested. This last experimental work is here shown. The stresses obtained are the sum of the residual stresses and the external applied stresses. Currently the group works in order to remove the effect of the residual stresses by means of tests on small metallic structures specifically built.

Keywords: X-ray diffraction technique, stresses measurements, metallic structure

Introduction

One of the most interesting challenges of the scientific community in the structural analysis field is the development of new non destructive experimental techniques (NDT). The research here presented deals about the applicability of X-Ray Diffraction technique for stresses quantification in metallic (steel) structures. The main problem in all cases for in-situ stresses measurements is that they have been already applied. Is not possible unload and load any structure in order to compare the results deducted by the techniques involved. Always the results are absolutes being not possible to check them with another stresses state of the analysed element. Considering that it is not possible to apply any load (or unload) to a real structure it must select the parameter that can be experimentally detected. The experimental value of this parameter should lead to the deduction of the stresses states. In this case the appropriate parameter is the separation "d" of the crystallographic planes of the steel phases (ferrite, pearlite,…). In other words, the "strain gage" employee is the family of crystallographic planes that contribute to the diffraction phenomenon.

All the elaboration processes (forming and finishing) of the metallic pieces introduce a set of stresses in the materials. A part of them has thermal origin whereas another part has mechanical origin. A proportion of these stresses remain in the material and they are denominated the Residual Stresses. In some cases its level can be similar to the yield stresses of the materials. For instance Fig. 1 schematizes the internal profile of residual stresses into a section of steel bars. By equilibrium conditions the area with sign under the stresses profile has to be zero. In most of the cases the residual stresses are confined very close to the surface of the element (a < 0.6 mm and b < 1 mm independently the diameter of the bar in Fig. 1). Fig. 2 shows the residual stresses profile in a pearlitic steel wheel (Fig. 3) introduced by a severe milling process recently obtained by the authors (the work is unpublished). In this case the material has been removed by means of electrolytic polishing until the appropriate relaxation of the residual stresses. The value of the residual stresses must be added to the values of the design stresses in order to know the true level of stresses in the structural elements. The experimental analysis on structures in service will obtain the sum of both stresses if the residual stresses are not previously eliminated. X-Ray Diffraction technique is widely applied for residual stresses measurements in metallic materials (ICRS2 1989, ICRS3 1991and S. Sánchez-Beitia 2009). In many situations they represent great benefits for the material behaviour because compressive residual stresses delay the crack initiation process due to corrosion or fatigue

[F. Aratraz and S. Sánchez-Beitia 1991). In the nuclear power plants or chemical factories it is imperative the quantification of the residual stresses (F. Artaraz, A. Gil, A. Irisarri and S. Sánchez-Beitia 1989) in all the critical elements (welded joints). However X-Ray Diffraction technique until now has not been applied in building or in civil engineering to measure the structural stresses. Within this industrial sector the most important applications of the technique is the evaluation of the residual stresses in prestressed steels. The hydrogen embritlement in the prestressed steel bars (rounds of 7 or 12 mm diameter) in construction is strongly influenced by the value of their residual stresses (S. Sánchez-Beitia and M. Elices 1986). Compressive residual stresses of 500 Mpa (0.3 times the yield stress) are normal values in these kinds of elements. Another application known is the quantification of the service stresses in this kind of steels (V. Monine, J.R. Tendósio and T. Gurova 2001)

X-rays do not make distinction between residual stresses and structural stresses. They detect the parameter that identifies the stresses state is to said the variation of the distance "d" between the crystallographic planes of the material. Since 2008 authors tries the introduction of X-Ray Diffraction technique in different applications for the construction sector (buildings and civil engineering). Potential applications for industrial heritage constructions are evident. Even more many ancient constructions in masonry contain recent metallic elements acting as reinforcement. The exact level of stresses in these elements is not well known or at least there exists a lack of knowledge about their exact role (S. Sánchez-Beitia et al. 2009).

The x-ray diffraction phenomenon is a "reflection" of an incident radiation over the crystallographic planes of material lattice which only takes place for a particular angle of incidence (θ_0). Unlike the diffraction, reflection has place for all the inclinations of incident beams. The diffraction phenomenon must be understood under quantum mechanics science explanation far the objectives of this paper. The relationship between the separation of the crystallographic planes (defined by their Miller numbers "h,k,l" with first order of diffraction) of a phase (d_0) and the inclination of diffraction (θ_0), is controlled by Bragg`s diffraction law:

$$2d_0 \mathrm{sen}\,\theta_0 = \lambda \tag{1}$$

where λ is the radiation wavelength. Stresses (residual or not) are manifested by a new value of the distance between the crystallographic planes "$d_{\varphi\psi}$" with regard to the value in the unloaded situation (d_0). This variation causes a variation of $\theta_{\varphi\psi}$ with regard to θ_0 according Bragg´s law. Differentiation of Bragg's law yields the relationship between the strain $\varepsilon_{\varphi\psi}$ (Fig. 4) of the deformed crystal and the angular shift of the diffraction beam ($\theta_{\varphi\psi}$ - θ_0)

$$\varepsilon_{\varphi\psi} = (d_{\varphi\psi} - d_0)/d_0 = -\cot\mathrm{g}(\theta_0)(\theta_{\varphi\psi} - \theta_0) \tag{2}$$

where φ and ψ are the angles (rotation and tilt) of the normal direction to the diffracting lattice planes in the fixed coordinate system (Fig. 4). In addition, considering a continuous, homogeneous and isotropic material (general conditions in the steel components except in very specific cases in which the material presents a texture) and considering small stresses gradients in the volume affected by radiation (a circle of 2 mm in diameter in surface and 0.1 mm depth) Hooke´s law allows the deduction of the following expression:

$$\varepsilon_{\varphi\psi} = \frac{1+\nu}{E}\sigma_\varphi \mathrm{sen}^2\psi - \frac{\nu}{E}(\sigma_{11} + \sigma_{22}) \tag{3}$$

where

$$\sigma_\varphi = \sigma_{11}\cos^2\varphi + \sigma_{22}\mathrm{sen}^2\varphi \tag{4}$$

Here σ_φ represents the value of the stresses that support the material in the direction defined by φ, $\psi = \pi/2$ (Fig. 4) whereas σ_{11} and σ_{22} are the principal stresses. Obviously it has been considered a plane state of stresses in the vicinity of the sample surface ($\sigma_{i3} = 0$). Eq. 1 is the "sen^2 ψ" law. The slope of the $\varepsilon_{\varphi\psi}$ vs "sen^2 ψ" function is directly related with the stresses on the surface of the material. Thus the x-ray diffraction equipment registers the values of $\varepsilon_{\varphi\psi}$ in each direction defined by the angles φ, ψ. The stress σ_φ can be calculated if the values of the mechanical constants of the steel are known (in normal applications these values can be taken from the bibliography).

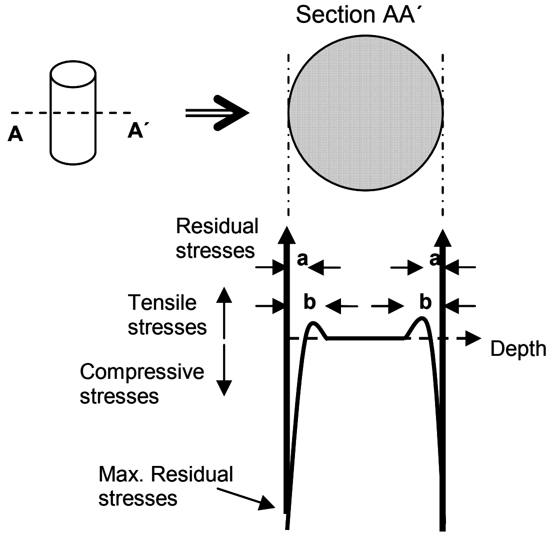

Figure 1: Conventional profile of the residual stresses inside steel bars

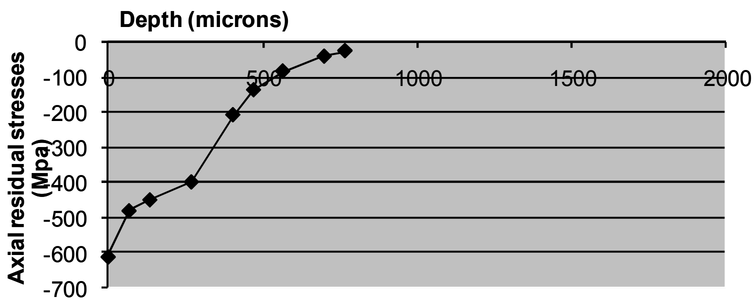

Figure 2: Conventional residual stresses profile in depth

Figure 3: Residual stresses measurements on a steel wheel

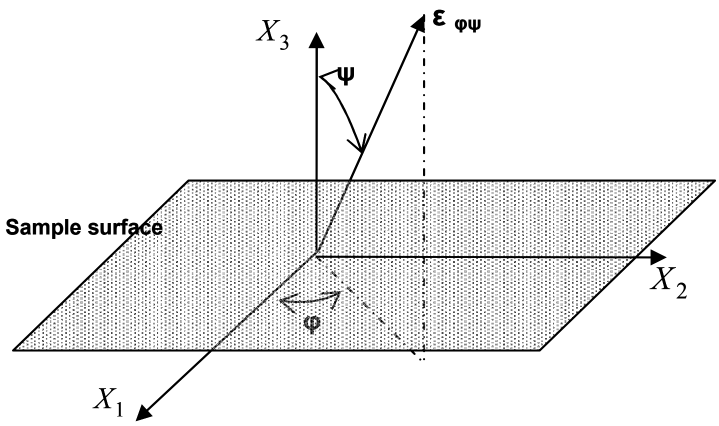

Figure 4: $\{X_i\}$ represents the reference system fixed over the sample whereas the direction of $\varepsilon_{\varphi\psi}$ is coincident with the normal to the diffracting planes

Experimental Tests

The measuring equipment is a standard Stresstech Xstresses 3000 with two different configurations. For laboratory tests the x.-ray unit can be attached to a metallic arm allowing the three spatial rotations and displacements (Fig. 5). For in-situ applications the x-ray unit is fixed to the tripod shown in Fig. 5 and 6. Until now it has been carried out three experimental tests. Firstly the stresses in a reinforcement bar of one of the towers in the Oporto Cathedral were quantified (Fig. 6 and 7).

The fixing system of the bars allowed the application of several external loads which has made possible to compare them with the results obtained by using X-Ray Diffraction technique. For the second experimental test two corrugated steel bars (10 mm diameter) were loaded under known stresses in a conventional tensile machine (Fig. 8, 9 and 10). Again the objective was the comparison between the applied loads and the results obtained by using X-Ray diffraction technique. These tests have been already published (S. Sanchez-Beitia et al. 2009). In all the cases the results obtained by x-ray diffraction correlate excellently with the applied loads. Recently the bars of a small metallic structure (Fig. 11, 12 and 13) have been tested. This experimental work is here shown. The structure is constituted by two simple structures connected by bolts (12 mm diameter). At top and bottom two plates have been welded to receive the load from the compression machine and four metallic profiles assure the vertical displacement of the set when it is loaded. Inclined bars have 28 cm in length and section of 10 x 30 mm^2 whereas the horizontal bar has 48 cm in length and same section. The connection system between bars generates an inclination of 40º for the inclined bars with respect the horizontal direction. Three known loads have been applied in a compression machine. In each load step the stresses in a bar of the structure by means of X-Ray Diffraction technique have been obtained. Unfortunately the structure broke at 9.000 Kp.

Figure 5: General sigh of the laboratory configuration

Figure 6: Load application at the bars in Oporto Cathedral

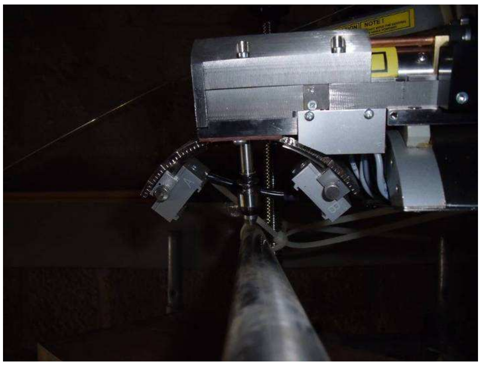

Figure 7: Equipment placed on the bar of the Oporto Cathedral

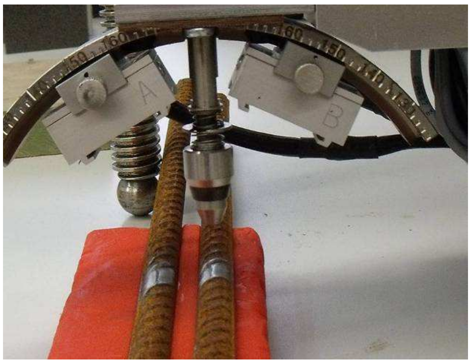

Figure 8: Sight of the calibration process before loading corrugate bars

Results and Discussion

Before start the load process the residual stresses in a inclined bar have been quantified (Fig. 12). The irradiated zone is the same along the experimental process (Fig. 13). The metallic structure has been loaded in compression to 1300 Kp, 5000 Kp and 7000 Kp. These loads correspond with 17 Mpa, 63 Mpa and 90 Mpa respectively for the stresses applied to the bar. Table 1 shows the comparison between the applied stresses and the stresses obtained by means of X-Ray Diffraction technique. Obviously the stresses measured by x-ray are the sum of residual stresses and the applied ones because the irradiated zone is included within the material affected by the residual stresses (Fig. 1).

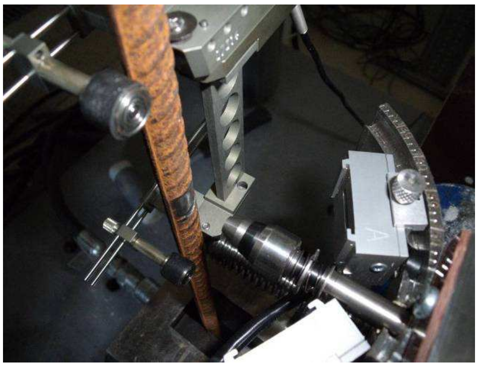

Figure 9: Measurement process on the corrugate bar in tensile machine

Figure 10: Measurement process on the corrugate bar in tensile machine

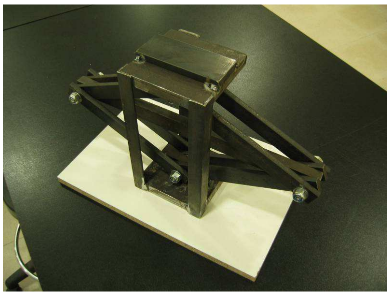

Figure 11: Sight of the metallic structure

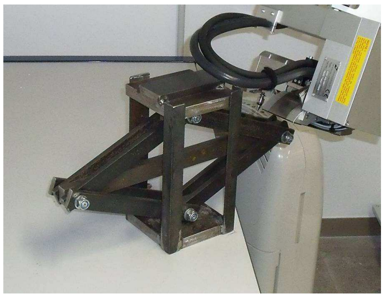

Figure 12: Calibration process before the process of load

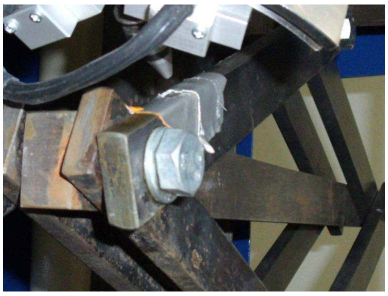

Figure 13: Measurement process over the structure under load

Table 1: Comparison between the applied stresses and the results obtained by means of X-Ray Diffraction technique

Stresses applied σ_A [Mpa]	*Stresses obtained by x-ray diffraction σ_R [Mpa]*	*Stresses obtained by x-ray diffraction removing the contribution of residual stresses [Mpa]*
0 (Residual stresses)	- 151.8 +/- 22.1 (Residual stresses)	0
- 27	- 173.9 +/- 22.6	- 22.1
- 63	- 217.3 +/- 28.6	- 65.5
- 90	- 251.3 +/- 16.5	- 99.5

The results obtained by means of X-Ray Diffraction technique correlate acceptably with applied stresses. This conclusion was expected because X-Ray diffraction technique is currently applied around the international scientific community for residual stresses identification. The innovation of this paper consists on the applicability of the technique to obtain the stresses states on structural elements (buildings and civil engineering).

Recently has been acquired a portable electropolishing equipment in order to remove the zone of material affected by residual stresses (0,6 mm in depth over a diameter of 5 mm in surface). Therefore next objective will be the deduction of only the external stresses. Once achieved this objective X-Ray Diffraction technique may be applied directly on any metallic structure in use. Even more it will be available to know both kinds of stresses. This calibration will end in coming weeks.

Acknowledgments

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References

[1] Artaraz, F, and Sánchez-Beitia, S (1991). "An unsuitable residual stresses state in train springs originated by shot peening." *Int, Journal on Fatigue*.

[2] Artaraz, F, Gil, A, Irisarri, A, and Sánchez-Beitia S (1989). "Residual Stresses generated in welded joints of SA CL1 steel." in *Proc. of the IAEA (Int. Agency of Atomic Energy), Meeting of specialists of nuclear power plants,* Buenos Aires (Argentina).

[3] Monine, V, Tendósio, J R, and Gurova, T (2001). "Study and service control of stress state of high strength steel cables used in prestressed concrete structures." *International Centre for Diffraction Data, Advances in X-Ray Analysis*, 44, 195-200.

[4] *Proceedings of the ICRS 2 (Int. Conf. on Residual Stresses),* Nancy (France), 1989.

[5] *Proceedings of the ICRS 3 (Int. Conf. on Residual Stresses),* Tokushima (Japan), 1991.

[6] Sánchez, B S (2009). "Stresses quantification in structural steel bars by X-Ray diffraction technique. PART I: Concepts," in *Proc. of REHABEND 2009 Congress,* 481-496.

[7] Sánchez-Beitia, S, and Elices M (1986). "Influencia de las tensiones residuales superficiales sobre la fragilización por hidrógeno en aceros eutectoides trefilados (in spanish)." *Rev. Iberoamericana de Corrosión y Protección*. Vol XVII (1), Enero.

[8] Sánchez-Beitia, S, Ramos, L, Lourenço, P, Elices, J, Lombillo, I, and Villegas, L (2009). "Stresses quantification in structural steel bars by X-Ray diffraction technique. PART II: On site measurements," in *Proc. of REHABEND 2009 Congress*, 497-509.