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The Intumescent Paint Layer's Thickness Influence on the Load-Bearing Capacity of the Steel Joints

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Abstract. In order to improve the steel structures' protection against fire, the intumescent paint method can be applied along with other methods. The intumescent paints layers numbers have to be optimized though. An uniform layer of intumescent paint, foreseen to protect the whole structure, represents both a higher cost and an uneconomical solution. The authors started examination on this problem, by analyzing one of the most recommended steel joints from the earthquake-proof criteria. The conceived and realized original electric furnace allows both a high-accuracy tuning/adjustment of the temperature and a good-stability of its, by means of the original electronic command. In order to perform high-accuracy and full-field monitoring of the displacements, the authors used a modern optical non-contact system, the Video Image Correlation one. The obtained preliminary results are very promising and will be continued in the next period by this international team.

Introduction

It is well-known fact that the steel structures present a relatively great disadvantage in comparison with the concrete structural elements due to the fact that the formers have to be provided with some additional fire protection systems. Otherwise, the steel members' load-bearing capacity becomes unacceptable low, when, during the fire, the temperature grow up over $550...600^0\,C$. One of these fire-protection modalities consists in the applying of an intumescent paint layer, which also presents the advantage of preserving the initial design of the structural elements (the principle of the functionalism, initiated by Bauhaus Architectural School). The unprotected steel members present an inherent fire resistance of about 15 to 30 minutes, which usually is not enough for saving the human lives and material goods from the buildings in case of fire.

According to literature [1,2] using the so-called Shape-Factor (Massivity) (see Eq. 1), can improve the intumescent paint's application significantly.

By definition [1], the Shape-Factor (Massivity) represents the ratio between the exposed surface area of the member per unit length A_m and the volume of the member per unit length V:

$$\chi = \frac{A_m[m^2/m]}{V[m^3/m]} \qquad (1)$$

In case of a member having unit length, this means in fact

$$\chi = \frac{L[m]}{S[m^2]} \quad (2)$$

the ratio between the exposed steel perimeter L and the steel cross section S.

In [1] there are several useful values and graphs regarding on the Shape-Factor, depending on the steel members shape and size, respectively the fire evolution (the corresponding temperature).

From the suitable structural elements' point of view, the hollow sections, especially those rectangular ones, present several advantages worth mentioning: an easy connection to the flat surfaces and consequently they are widely applied for columns and trusses.

Supplementary, from the fire protection point of view, as it is stated in [2], they offer, between others: a reduced surface area (e.g. the square hollow sections have about 2/3 of the same size ***I***-section shape's area); the corresponding trusses will present smaller cross-sections due to their higher structural efficiency; the absence of some re-entrant corners makes the intumescent paint application, respectively the fire protection itself, easier, sure and durable; they present less surfaces (only four) for painting than the ***I***-sections, and consequently, less material and less labour needed.

Obtained results in the electric furnace

In reference [3], the authors (based on the previously-, and meticulously - care prepared research results of Kurobane and Shinde) analyzed several widely applied beam-to-column connections, which were the improved ones from seismic behaviors point of view.

Subsequently, in [4], the authors started to investigate the cheapest one from fire-resistance point of view, at a reduced scale model (approximately at 1:5), presented in Figure 1.

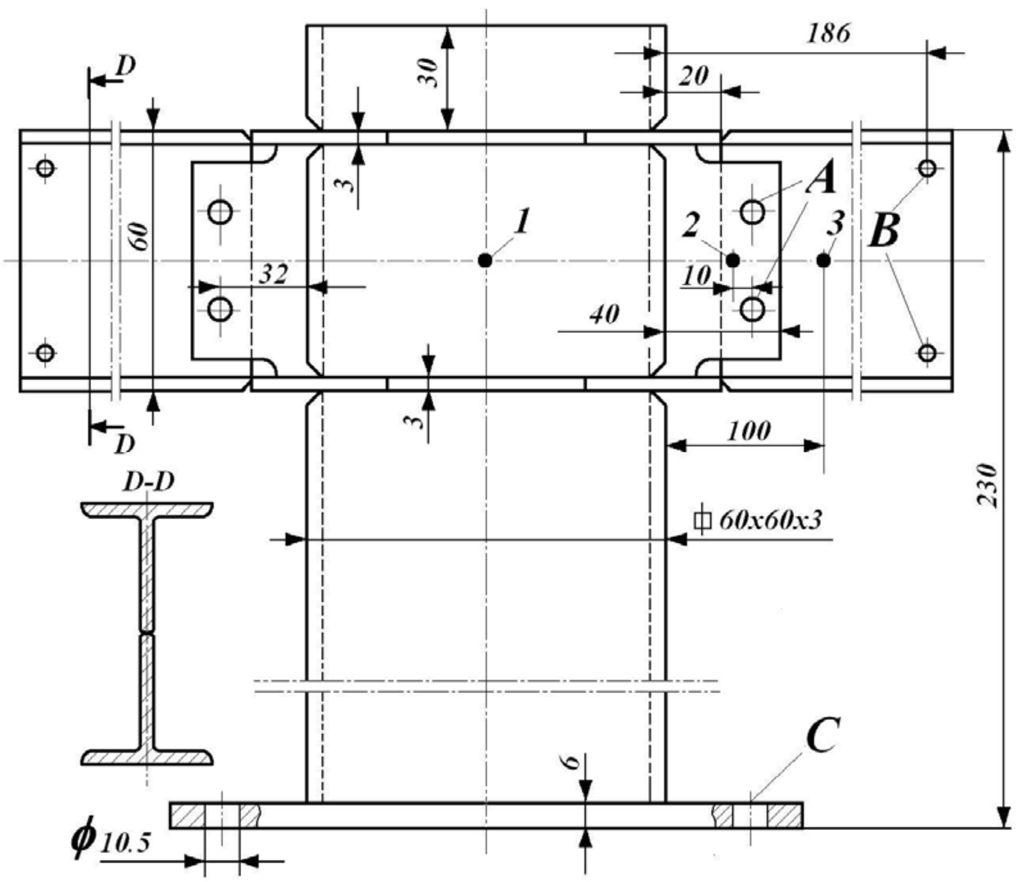

Fig. 1 The analyzed beam-to-column connection; A - the screw-connections; B - the holes for external mechanical loading; C – the holes for external connection [4]

In the first step of the investigation, the authors tried to find out some optimal relationship between the intumescent paint layer's thickness and the thermal field's uniformity of the joint during a simulated fire. They provided the joint (beam-to-column connection), previously of applying the paint, with thermo resistors: ***#1*** - in column; ***#3*** - in adjacent (here: horizontal) member, respectively in ***#2*** - the connection zone, presented in the same Figure 1. One other one: ***#0*** - was positioned in the electric furnace near the steel specimen.

The original electric furnace, having an electronic control system, was able to reproduce the ISO-curve (the so-called "standard fire-curve"), defined in ISO 834. Fig. 2 illustrates its electronic-controlled thermal stability, together with the corresponding polynomial approximation. The presented thermal oscillations are less than 45 seconds length.

Based on the recommendations from literature, mainly from [1], two different types of intumescent paint-protections were applied:

I. with uniform (three layers) paint, respectively

II. with differentiate layers (two, respectively three ones) of paint.

For this second case, based on the Eq. 2, the Shape-Factors were calculated:

- for the column $\chi = \frac{L[mm]}{S[mm^2]} = \frac{4 \bullet 60}{684} = 0.350$ was obtained, respectively
- for the horizontal members $\chi = \frac{L[mm]}{S[mm^2]} = \frac{2 \bullet 116}{2 \bullet 226} = 0.513$.

Due to the fact that these Shape-Factors present the ratios $\approx 1/3 = 2/6$, respectively $\approx 1/2 = 3/6$, the authors decided to apply, in this second case, two equal thickness layers on the column, respectively three on the horizontal members.

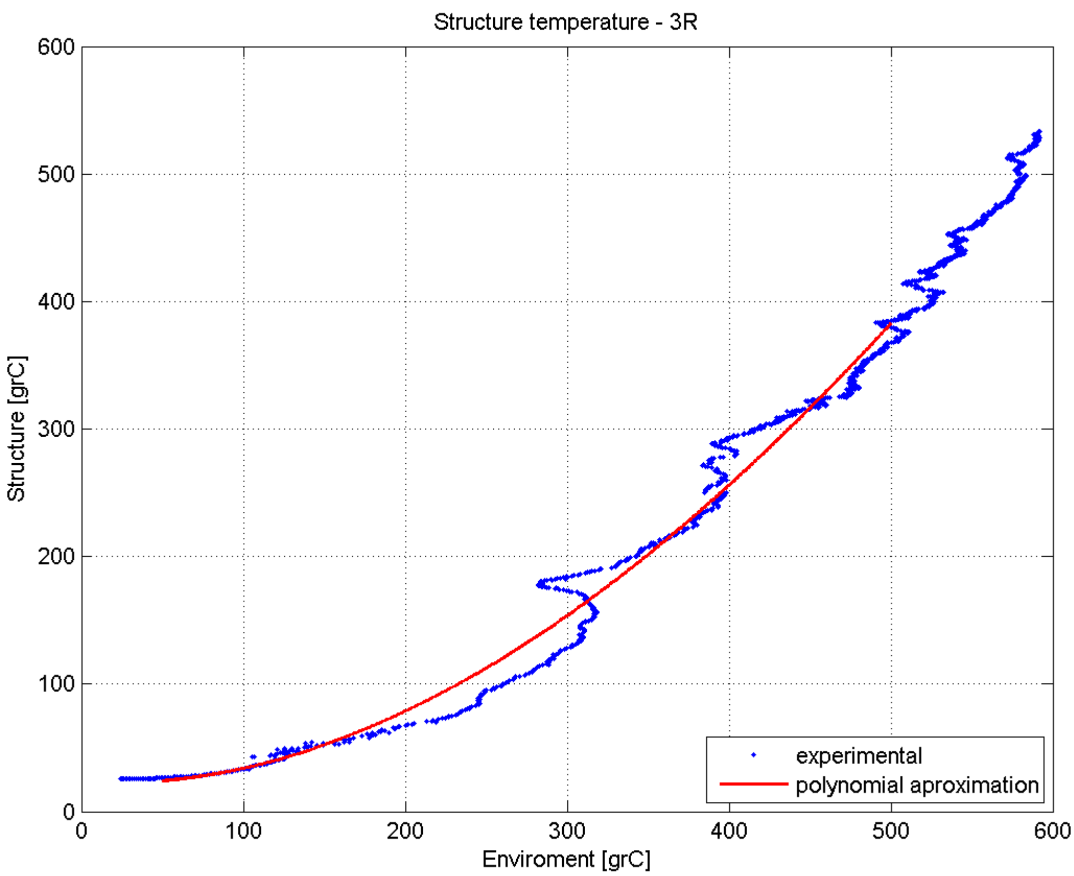

Fig. 2 The electric furnace's performance, considering the temperature control/stabilisation, respectively the polynomial approximation of the achieved temperatures.

Figure 3 presents the theoretical displacement at level ***B***, considering only the Young's modulus changes depending on temperature, respectively infinite stiffness of the connection points. The nominal total load was F = 10 *kN*, applied in these two points ***B***, when an uniform number of layers are applied (unprotected structure, respectively 2, 3 layers). Of course, by applying different numbers of layers on different members, one can obtain better bearing capacity out of the system.

In literature, a well-known relationship, which is applicable for temperatures in range of $T \in [0,\ 600]^0 C$, is given:

$$E(T)[GPa] = e_0 + e_1 T + e_2 T^2 + e_3 T^3, \qquad (3)$$

where $e_0 = 206.0$; $e_1 = -0.044326$; $e_2 = -3.502 \cdot 10^{-5}$; $e_3 = -6.592 \cdot 10^{-8}$.

The code "***0R***" was applied for the unprotected structure.

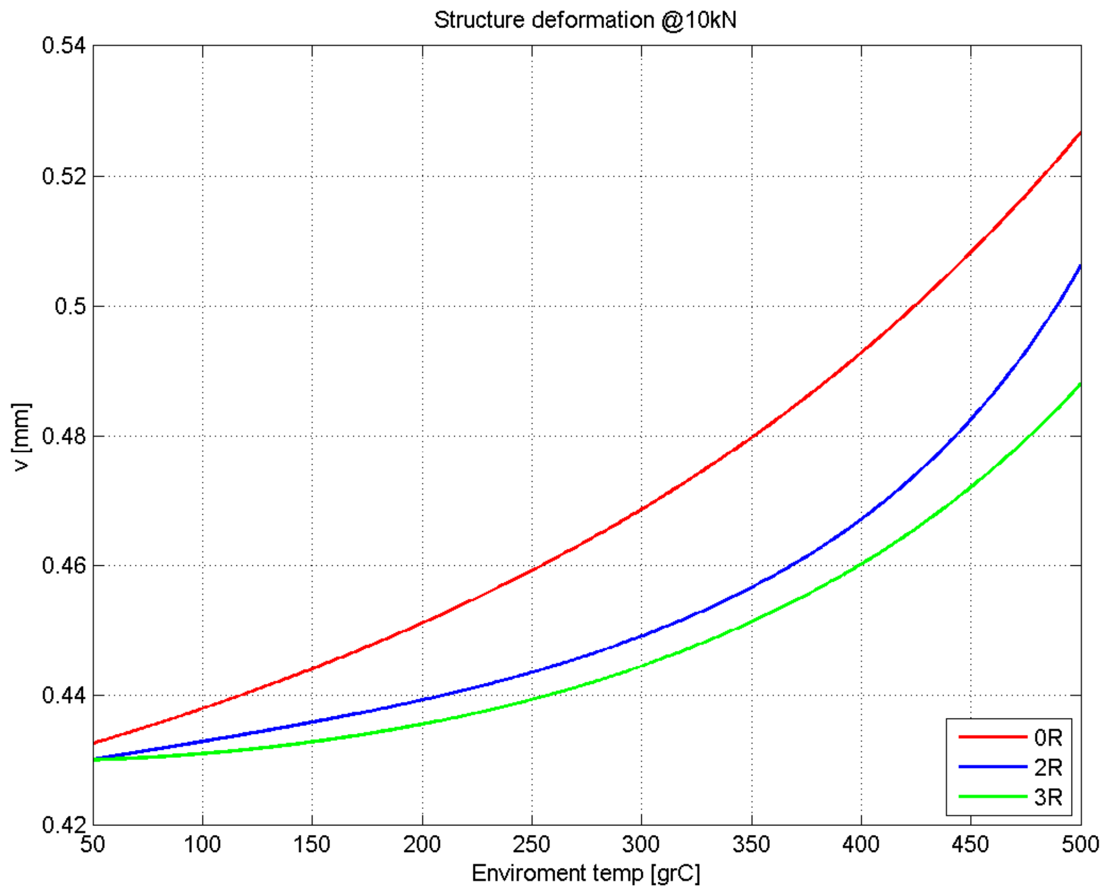

Fig. 3 Theoretical displacement at level ***B***, for uncovered (***0R***), with two (***2R***), respectively three (***3R***) uniform layers of intumescent paint, based on the Young's modulus variation with the temperature; the applied force was considered 10 *kN* and only the cantilever beam deformation was taken into the consideration.

The VIC-experiment preparation

In order to perform a high-accuracy evaluation of the displacements, the authors choose the Video Image Correlation system from ISI-Sys GmbH, Kassel, Germany; its 3D version (VIC-3D) [5,6], which they feel that fulfills the proposed requirements of the investigations as good as possible.

Among other facilities of the system one can mention:

- it is a contact-less optical method;
- it is able to eliminate the rigid body movements from the achieved values;
- it presents a good accuracy in 3D investigations of the displacements field's components (up to approximately 1 μm);
- it can offer not only the displacements field, but also the corresponding strains, too;
- it allows a large range of the measured values of the displacements (starting from some microns up to several cm;
- it allows the data extracting in different formats (e.g. in csv-files etc.);
- it allows a superposing of a metric nod mapping, similarly with the FEM-analysis ones;
- it presents a good stability, allowing high-accuracy measurements in operating/ working/industrial conditions.

Basically, the system consists of two high-resolution video cameras, fixed on a very rigid Aluminium connection rod (see Fig. 4), which is mounted on a very stable tripod.

The investigated object's surface is sprayed in advance with a water-soluble paint, in order to obtain a non-uniform dotted surface; the size of dotes depends on the tested/investigated surface magnitude.

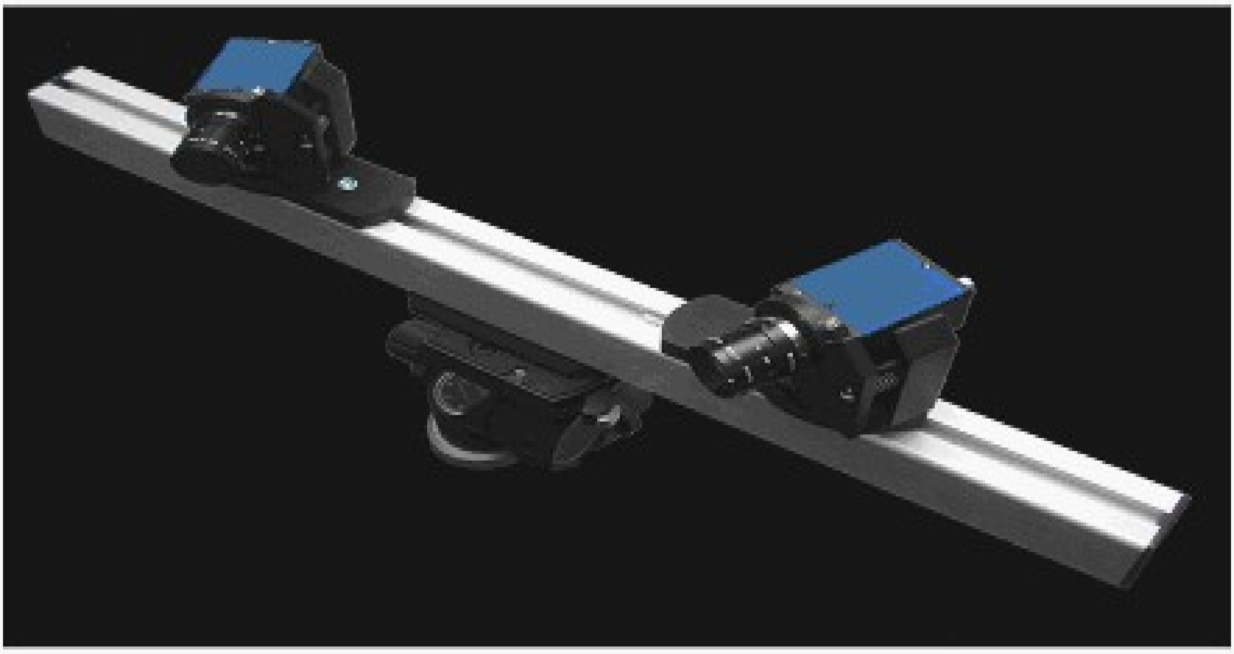

Fig. 4 The main parts of the VIC-3D system [5,6]

After a calibration, using some special targets (Fig. 5), the cameras will perform the image acquisition in an [*nxm*] matrix of pixels, firstly for the unloaded specimen and secondly for the loaded one. On the unloaded specimen's images one has defined the Area of Interest, the proper Sub-set (see Fig. 6, where this Sub-set consists of $5x5 = 25$ *pixels*), the optimal step-magnitude for the Sub-set, so that one can evaluate the whole image by moving the Sub-set horizontally and vertically over it.

For a nominal position of the Sub-set, the software will determine an unique grey-code which belongs to the median pixel and then the 3-D coordinates of this pixel are measured with a high accuracy. By analyzing the image captured (corresponding to the unloaded state of the object), that will be substituted by means of these median pixels of the Subsets. A similar analysis will be performed for the captured left-, and right images throughout the whole loading stage. The software will compare the 3D displacements at the representative median pixels with those belonging to the initial stage and then it will draw-up the corresponding displacements vectors.

Consequently, it becomes possible to follow (in 3D) not only the displacements, but also the corresponding strains at the significant points in the Area of Interest.

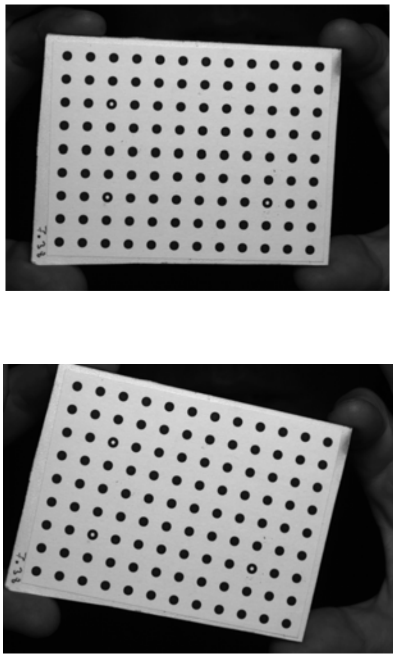

Fig. 5 Different stages of the calibration process

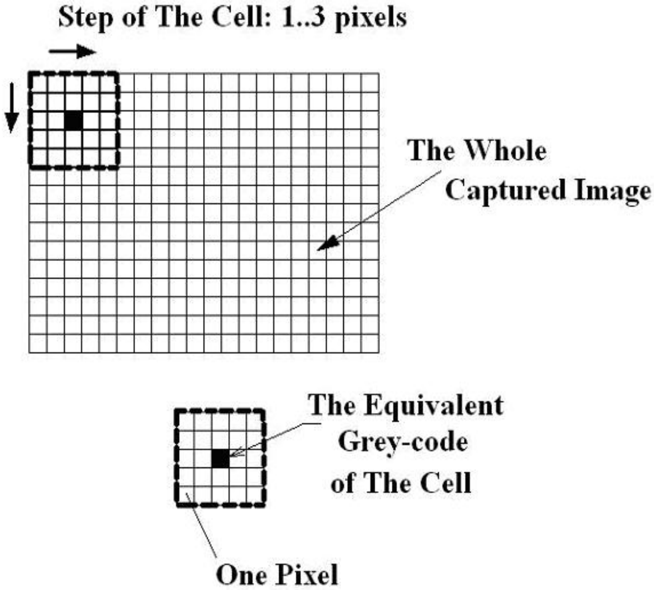

Fig. 6 The measuring principle based on the scanning procedure [5,6]

Experimental results obtained using VIC-3D

The above-described VIC-3D system was used by the authors in order to compare the theoretical displacements with the real ones. The authors monitored the vertical displacement of points ***B*** of the horizontal members, where the vertical loads *F/2* were also applied.

In the theoretical calculus, for the horizontal members, the ideal connection (having infinite stiffness at the column level, considering a cantilever beam with fixed support on the column); the environmental temperature and a progressive (practically static) loading up to the nominal value were considered.

Based on these and applying the common relations from Strength of Materials, the displacements at level ***B***, corresponding to the progressive loading, were calculated. In Fig. 7 the straight line offers these results.

This theoretical displacement, presented in Fig. 7 doesn’t include the column’s shortening due to the applied total load F, which is given by the well-known relation

$$\Delta\ell = \frac{F \cdot \ell}{E \cdot A} = \frac{10000 \cdot 230}{2.1 \cdot 10^5 \cdot 684} = 16.01 \cdot 10^{-3}\, mm = 0.016\, mm\,. \qquad (4)$$

Even this shortening is very small, but for accurate calculus one has to be taken into the consideration.

Using the VIC-3D system, at the same level, quite different values were obtained, due to the fact that the material isn’t ideal (having different mechanical characteristics in comparison with those from literature), and also the connection with the column wasn’t ideal (with an infinite stiffness). Other motive of the obtained greatest value by VIC consists of the fact that the beam’s end is cut off, and consequently presents a lower stiffness than the other parts of the beam.

Also, one can observe the connection’s modifications, by those supplementary curved portions, because these connections were realized using both welded parts and screw-fixations (2 pieces M10-screws at level ***A***).

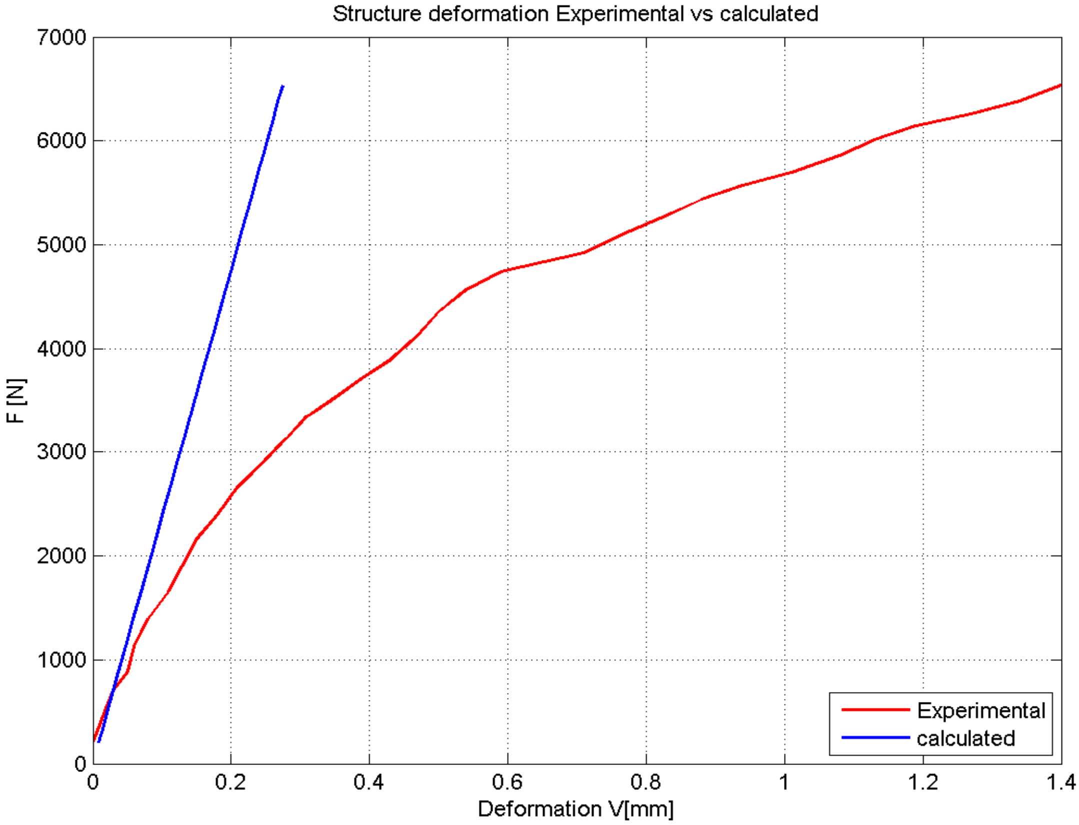

Fig. 7 Structure deformation at room/environmental temperature

Figure 8 offers an illustration of the VIC-3D analysis, where in a color-code one can evaluate the real displacements of the different cross-sections of the horizontal beam. In the upper right corner is mentioned the applied total load F [N].

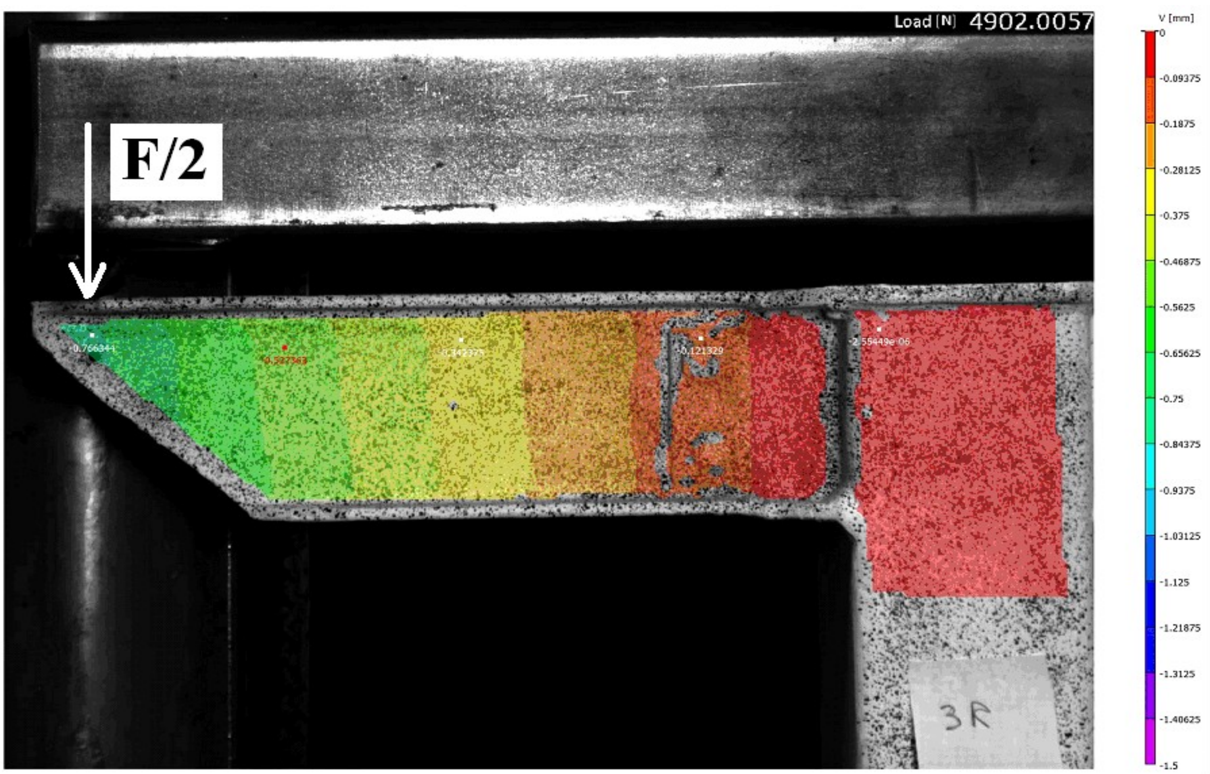

Fig. 8 An intermediate stage (displacement field) of the loading process by VIC-3D

Summary

The authors have developed/elaborated a new and efficient method to establish the intumescent paint fire-protection behavior.

Based on the advantages of this original electric furnace, it became possible to perform high-accuracy experimental investigations on the different type of joints, mainly in vicinity of the connection beam-to-column, foreseen with different number of layers of the intumescent paint.

By combining the thermal results obtained in this furnace (more exactly: the temperature modifications depending on the different number of layers) with the results of the static loading of the joints (the displacements, respectively the modifications of the stiffness) both in furnace and in common tensile-compression testing machines, some very useful results are expected.

The main advantage of this new approach consists in providing good and realistic information on the elastic properties of the actual physical joints used in steel structures.

Considering the measurement strategies presented, one can also determine the optimal thickness of the intumescent paint and consequently a better price for these fire-protection activities can be obtained.

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