Comparison of FEA and Experimental Results for a Steel Frame Connection

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Abstract: The paper presents the results and the similarity between the experimental test and FEA of a steel frame connection. The same connection is analyzed in two situations. The second case analyses the connection having some of the elements strengthened in order to increase the capacity of the specimen. The analysis is performed using solid finite element and is compared to the experimental test performed in the laboratory. Several considerations, such as identical conditions for force definition, have to be taken into account in order to obtain good results.

Key-Words: deformed shape, strengthen, strain gauge, boundary conditions, stresses.

1 Introduction

Steel structures are used in different fields of civil engineering as: roofs, halls for production, exhibition halls, towers for radio and TV transmission, pipes, bridges, foot bridges, high-rise buildings.

Maintenance, repair and strengthening of existing steel structures are important activities for civil engineers. Many experts and consulting engineering firms are concerned with analysis of existing steel structures and the design and execution of repair and strengthening measures.

Steel structures are found in the world in many fields. A part of these steel structures are near the end of their service life. Processes of the deterioration are the result of steel corrosion, deficiency and inclusions in welding, cracks in the welding, buckling of elements and local deformations of elements, defects in micro structure of steel which have generated by different causes.

The deterioration processes, their causes and the counter-measures to remove, reduce or retard their actions, the methods to repair the damage that they caused, have been frequently analyzed for steel structures and steel bridges.

Repair measures aim to re–establish a structure’s capability to accept the actions for which it was designed with sufficient safety and durability. Repair measures can usefully extend the service life for deteriorated steel structures. The need of repair may also arise due to errors in design, construction and maintenance, or due to accidental damage.

The usual aim of strengthening of existing steel structures is to allow for increased actions. The need to strengthen a structure may also impose higher functional requirements than those anticipated in the original design. Steel structure should be replaced only when it has been established that repair or strengthening measures are not technically feasible or economically reasonable.

2 Diagnostic of steel structures

Actual procedure for diagnostic of steel structures is obtained by long experience in reconstruction and monitoring technical conditions, making diagnosing activities systematic, unifying methodology of diagnostics and informing on necessary equipment by instruments. It assumes gathering of continuous documentation about the structure as a background for proposing of a way for reconstruction.

Existing steel structures can be affected by different (various) deteriorations. Repair interventions can vary considerably in scope. Minor interventions should be undertaken during routine maintenance. Structures must be cleaned regularly of mud, weeds, debris, salt and other aggressive substances. The aggressive substances can initiate the progressive deterioration of steel structures. Drainage systems must be regularity cleaned and repaired.

Repairing of small deterioration due to corrosion is common for steel structures. In these cases surface layer or paint cover is thin and steel has no protection.

When more complicated repairs are made to an area of major damage the process is called rehabilitation. Replacement of corroded bars is such a rehabilitation repair. The replacement bars are welded to bound existing bars. It should be noted that, during performing of this type of repair, the structure may need to be temporally supported.

Cracks in the weld should be backfilled by additionally injected weld, which increases the durability of the structure. The repair can be controlled by ultrasonic devices and by coring.

Before a decision to strengthen is made, the remaining capacity of structure should be determined. After technical expertise, alternative measures to increase the capacity of structure should be considered. Strengthening is usually the most serious intervention. When the live load is small in comparison with total actions, after strengthening additional live load can be supported. This is the case when the dead load is relatively high, as is typical for concrete structures. The safety condition of structure can be written as the effects of actions S_d should not exceed the corresponding design values of structure’s resistance R_d,

$$S_d \leq R_d \tag{1}$$

If the effects of actions on the structure were to exceed S_d, the structure will need to be strengthened accordingly.

Strategies for strengthening existing structures can be classified into two groups.

The first group consists of strengthening methods which will increase live load without increasing resistance. Increasing live load does not call for increasing the design values for actions’ effects, Sd. Without any increase in the resistance of the structure, R_d remains adequate. This can be achieved by decreasing dead load. This method is frequently applied, as it does not involve the complexities of an actual strengthening intervention in the full sense of the word. Decreases the dead load can be achieved in the buildings by replacing existing heavy floors and walls with lighter elements, or for bridges, by replacing heavy pavements with lighter ones. Reduction of dead load is often applied when additional stories are built on existing structures. In such cases, the additional dead load of the new construction should be taken into account. IT should also be noted that, due to the greater partial safety factors required for live load than dead load, the additional live load is less than the removed dead load.

Decreasing the span of existing structure is possible to allow an increase in live load that will be sustained by new supports. This method is applied when overall dimensions and aesthetics allow. Decreasing a span can be achieved by expansion of supports.

Changing the structural system is highly versatile. Using a new supplementary structure is possible to have a higher capacity of existing structure.

Additional pre-stressing is an efficient way of strengthening of structures. When additional pre-stressing is applied, the stresses in existing structures should be precisely known. Care should be taken that tendons (ties) are sufficiently tensioned and corrosion will not develop.

The second group of strengthening measures consists of those which increase the design values of resistance of structure Rd.

Increasing the cross section is a simple and frequently applied strengthening method;

Additional elements on the cross transversal section of elements is a very efficient method of strengthening.

Additional reinforcement in the tension zone is a very efficient method of strengthening. Strengthening of circular cells in a steel silo has been successfully performed by adding reinforcement which has been protected with steel on outside of the silo.

Adding bonded steel plates is a good strengthening measure that has grown widely in recent times. Bond between the additional steel plate and the existing steel structure can be successfully achieved by welding or bolting. Instead of steel plates, other materials can be used. Bonded carbon-fiber or reinforced plastic plates have been used successively for this purpose.

Replacing structural members refers to strengthening of a steel structure by replacing structural members or by adding new members without removing existing ones. A convenient solution for strengthening a steel structure is to replace the existing deck. The new deck has been bonded to the existing girders by anchors and sealed with weld or with epoxy mortar.

A footbridge with a suspended deck has been strengthened by new steel hangers, without removing the existing pressed ones.

3 Description of the experiment

All these measures are considered due to a rational thinking and an engineering point of view. But, these measures need to be analyzed and simulated numerically and tested in the laboratory. The present paper makes a comparison between the results obtained in the laboratory and the analysis using finite element method. It is analyzed the consolidation of a frame welded connection with finite element method and experimental results obtained using electric resistive tensometry method. The welded joint was obtained from HEB cross-sections.

First, it was tested a welded beam to column connection as shown in Fig.1. The force was applied normal to the column. The strain gauges gave the results for each step of 100kN. The final value of force P was 2000kN in order to avoid yielding in the assembly. This was necessary because the second test would have been performed on the same sample and the plastic deformations would have given inaccurate results.

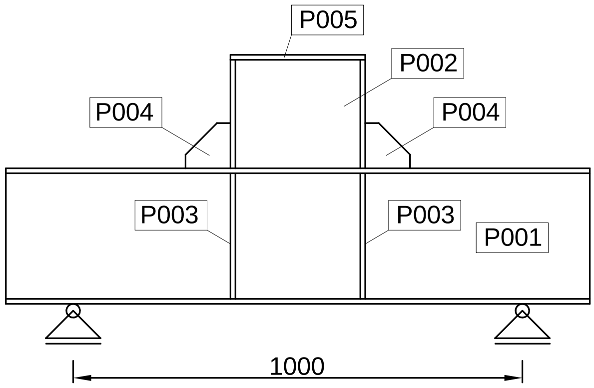

Fig.1 Initial experimental connection

The parts of the experimental connection are presented in Table 1.

Table 1

Part	Cross-section	Length [mm]	Material
-0-	-1-	-2-	-3-
P001	HEB300	1300	OL52 (S355)
P002	HEB300	150	OL52 (S355)
P003	Pb140x10	240	OL52 (S355)
P004	Pb100x10	100	OL52 (S355)
P005	Pb300x25	300	OL52 (S355)
P006	Pb240x10	1300	OL52 (S355)
P007	Pb240x10	460	OL52 (S355)

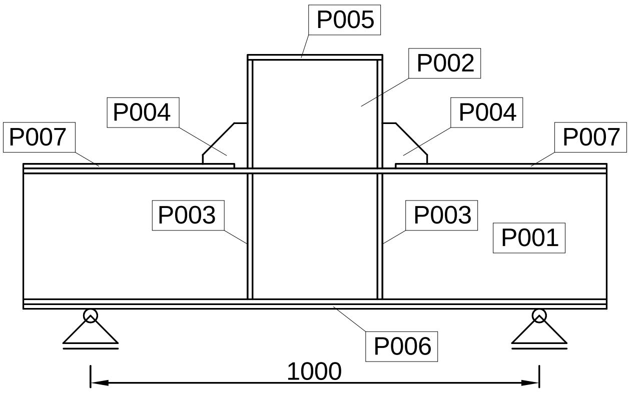

Fig.2 Strengthened experimental model

The strengthened experimental model is presented in Fig.2. The difference between the two models is the plates welded on the exterior of each flange denoted P006 and P007, in Table 1.

The strain gauges were put on the model as follows: two on the beam's web, two on each of the beam's flange, two on the column's web for the strains developed normal to the force's direction, two on the column's web for the principal directions and one for strain in the direction of the force and there are three more strain gauges placed on one of the columns flange for the strain normal to the force's direction. A sketch of the gauges placement is shown in Fig.3.

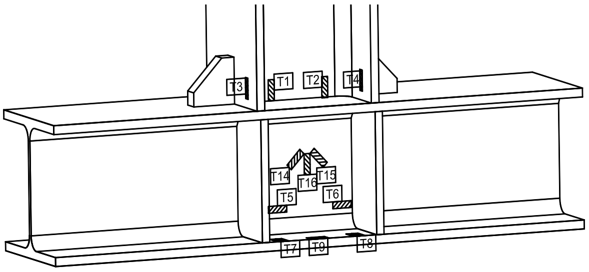

Fig.3 Gauges position

The main aim is to use the finite element method to observe if the results obtained in practice are the same with the ones simulated with computer programs. The advantage of such comparisons is the fact that, for the future, there is not necessary to spend money on experimental tests (unless necessary).

For the simulated analysis, the models were created as solids like in Fig.4.

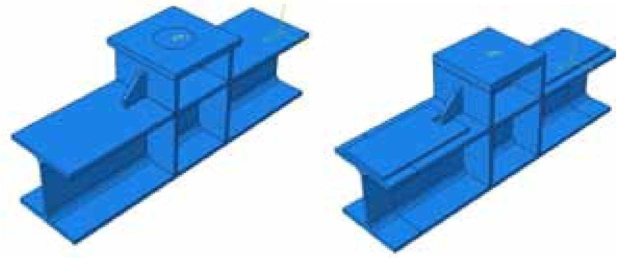

Fig.4 Modeled connection

4 Results of FEA

The finite elements were chosen to be arranged in the mesh as structured elements, but, at the intersection of an element's web with the flange, there cannot be discretized only with tetrahedron elements. This happened because the cross-section of the profile was modeled with the profile's radius between the web and the flange and not by plate joining. Because the part between the straight flange and the straight web was limited by three surfaces the meshing resulted with much more distorted elements. For this reason the entire profile was meshed using tetrahedron elements.

The boundary conditions were defined on surfaces, reducing first the translations on the vertical direction. The analysis did not reach a final analysis so the boundary conditions were changed. The displacement was reduced on both horizontal directions. The error might have occurred because this non structural mesh is not symmetrically with respect to all three axes. The bond between the elements was considered to be “tie”. The application of force was similar to the one applied in reality, a circular surface of 15cm diameter.

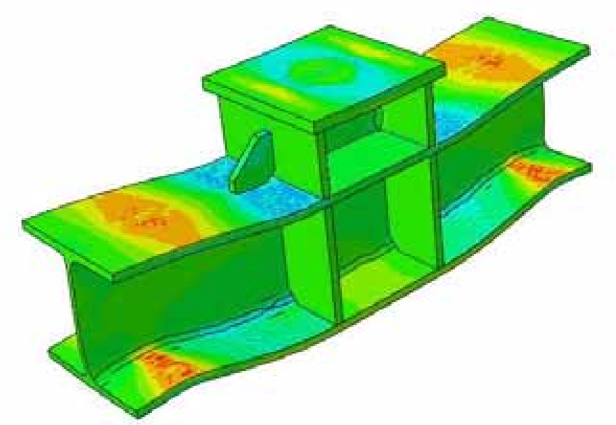

Fig.5 Deformed shape for initial connection

In Fig.5, the deformed shape of the first model (un-strengthened) also shows the stresses in longitudinal direction of the column. Red represents the tension and blue means compression.

Fig.6 shows the same stress at the same force applied on the plate. Also the color representation is the same as mentioned before.

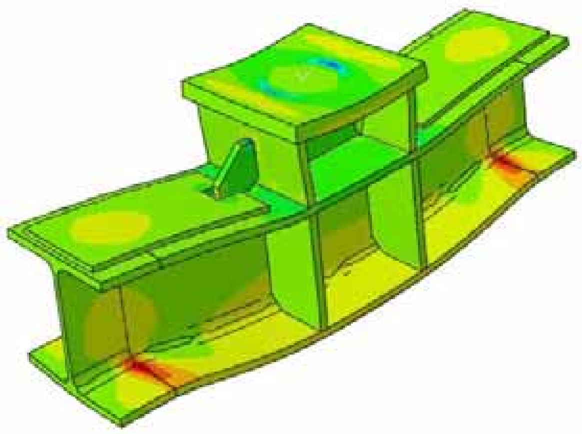

Fig.6 Deformed shape for the strengthened elements

From the two figures it can be seen that the models have the same behavior but the areas where the stress was maximum, are now smaller or gone, meaning that the connection can still be loaded until it reaches the yielding point. Another thing that can result from the analysis is the fact, although the strengthening parts on the upper flange of the column are not continuous, there is no stress concentration in the nearby of the welding between the column and the beam.

In the first situation, the location where the stresses have high values, are represented by small areas. These locations are: the supports of the model, the corresponding zones but on the other flange, the vicinity of stiffeners.

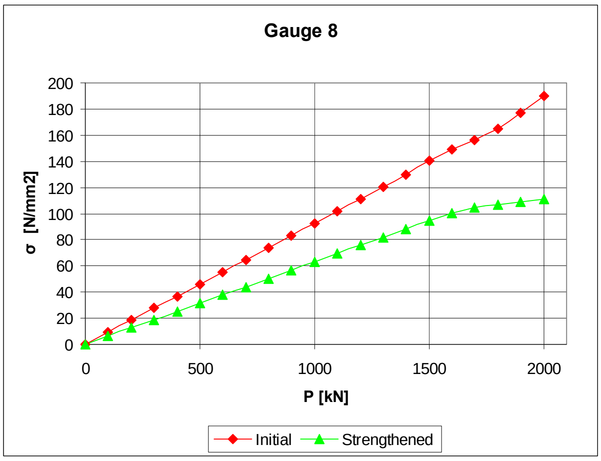

Fig.7 Results for gauge 8

In the second case, the areas, with close values for the stress, are larger meaning that the distribution of stress is more uniform and the location of yielding stress can be seen only in the support surfaces. The circular surface has also yielding points because the bending of the column had an influence on the bending of the plate welded to the beam. The same print could be seen on the experimental specimen, where the force was distributed finally through two areas apart from each other due to the detachment of the center of the plate from the pressure cylinder.

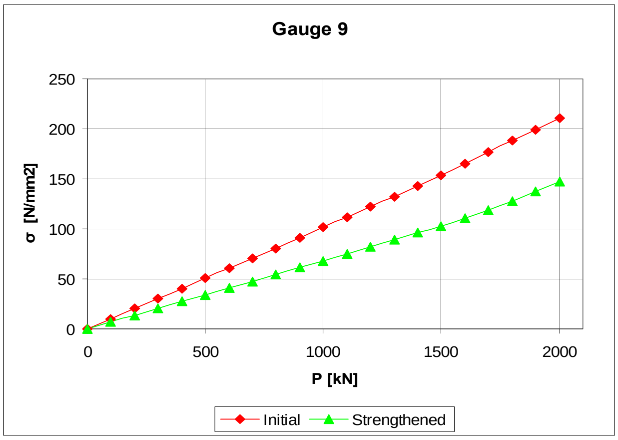

Fig.8 Results for gauge 9

Mainly, the stresses in the strengthened elements are less than for the first case, as it can be seen in the charts in Fig.7 and Fig.8. The rhombic filled line represents the values for the un-strengthened model and the triangle filled line represents the model with consolidation plates.

Fig.7 and Fig.8 show the stress of gauges 8 and 9 which are positioned on the lower flange of the column. Here, the stresses are reduced by 25-40%.

Most of the gauges present the same behavior but as the stresses needed to be distributed to the supports, there are locations where the stresses exceeded the values obtained in the first analysis model. A special attention should be paid to these zones as they can reach the yielding point before other main parts of the element.

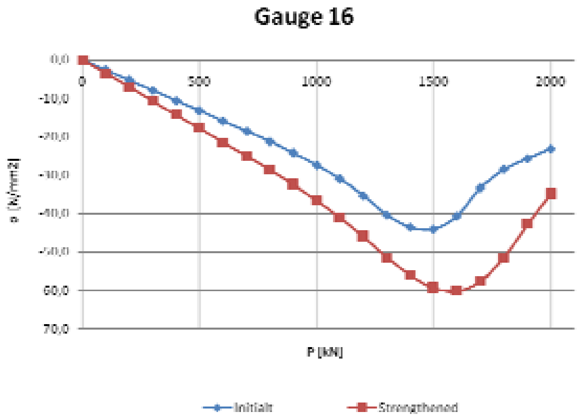

Fig.9 Results for gauge 16

Fig.9 shows the values obtained in the location of gauge 16, placed on the web of the column. It can be seen that the stresses in the case of un-strengthened model are less than the values obtained in the second case. It results that the web of the column is more stressed, but the values are not very high.

The same effect can be observed in the following figures.

Fig. 10 presents the stresses on the vertical direction for the un-strengthened model.

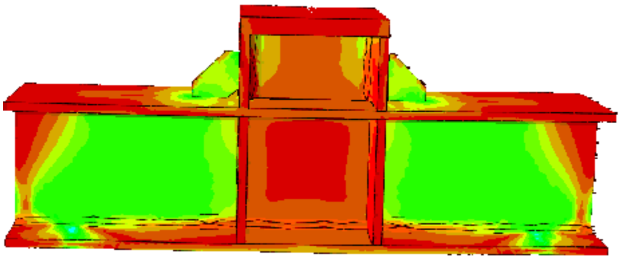

Fig.10 Stresses Syy for initial connection

Fig. 11 presents the stresses on the vertical direction for the strengthened model.

For the un-strengthened model it can be seen that the stresses, which reach high values, cover a larger area (green), in the web of the column, than for the second case.

The panel between the vertical stiffeners of the column shows a larger area for the higher stresses, in the first, un-strengthened model than the second model.

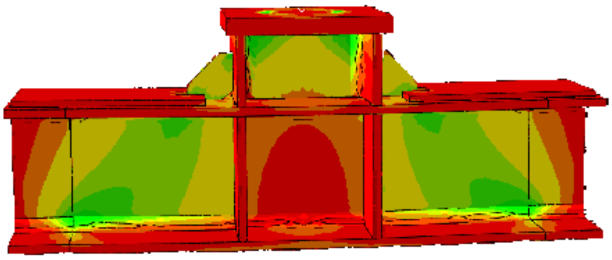

Fig.11 Stresses Syy for strengthened connection

5 Comparison to experimental test

The above results were obtained from finite element analysis, but they have to be checked and compared to values obtained from the real experimental test in order to validate the solution.

The stresses were obtained using the values indicated by the strain gauge at every 100kN step and using the Young's Modulus E with the value of 2.1e5 MPa.

For the experimental test of the joint, it was used a universal testing device with maximum load of 3MN, type ZD300. This is equipped with a bending device with roller supports which allow the positioning of the load at middle span as shown in Fig. 12.

The material's properties were obtained from a 100kN universal testing device, type ZD 10/90.

For the resistive tensometry it was used a special data acquisition system, type ESAM Traveler 1

Fig.12 Experimental stand

The lateral view for the experimental specimen is presented in Fig. 13 as well as the positioning of the strain gauges and the imprint of the pressure cylinder.

Fig.13 Experimental specimen

The next figures show the stress vs force distribution for different positions of strain gauges.

Gauge number 8 is positioned at the lower flange of the column so the maximum stress has the direction of the column. In Fig.14 there should be compared the red line (rhombic filled) with the blue line (triangle filled). These two present the results obtained for the first test. Red line is obtained from finite element analysis while the blue line is obtained from experimental test. It can be observed that the values are very close and they follow the same pattern.

The other two lines represent the results for the strengthened experiment. The green line (triangle filled) is obtained from finite element analysis and the magenta (circle filled) is obtained from the experimental results. As in the case of un-strengthened test the two lines follow the same pattern and have close values.

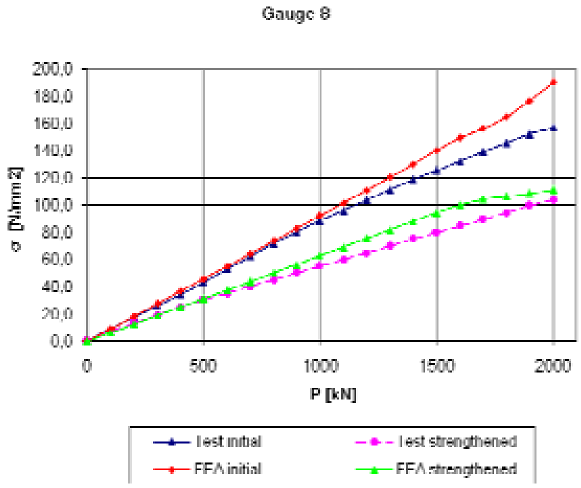

Fig.14 Results for gauge 8

The lines in Fig.15 and Fig. 16 have the same legend and it can be seen that the same conclusions can be drawn as presented for gauge number 8.

Gauge 7 and 9 are positioned also at the lower part of the column's bottom flange, under each stiffener.

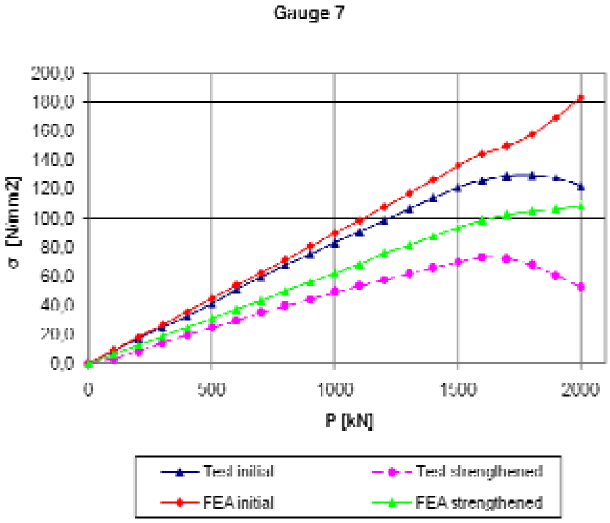

Fig.15 Results for gauge 7

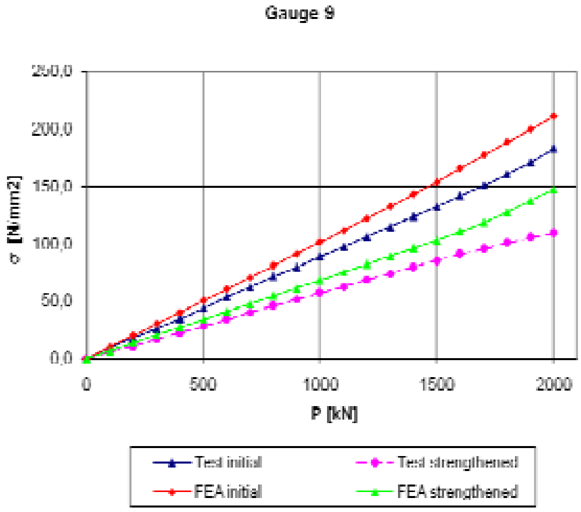

Fig.16 Results for gauge 9

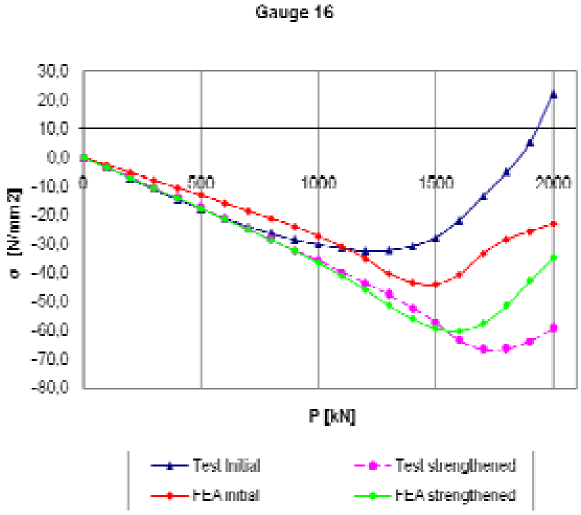

Fig.17 Results for gauge 16

Gauge 3 is positioned on the left flange of the column, inside the cross-section.

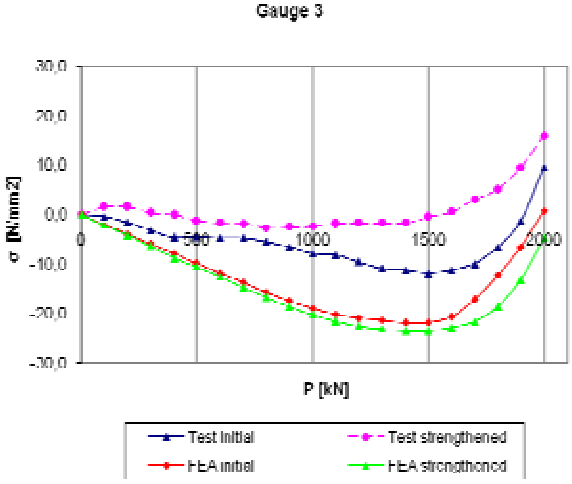

Fig.18 Results for gauge 3

Next figures present stresses in the un-strengthened and strengthened situation.

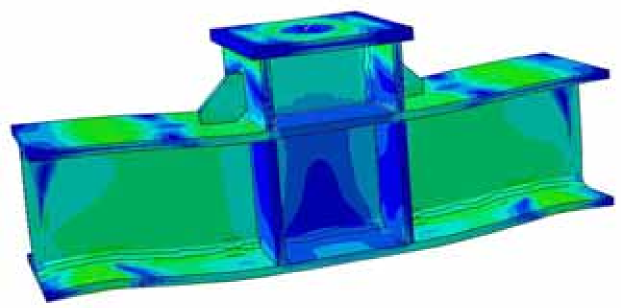

Fig.19 Stress Mises (initial)

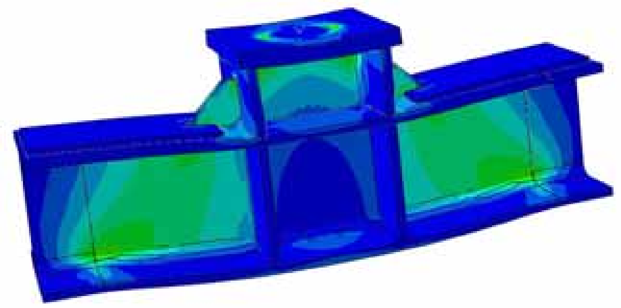

Fig.20 Stress Mises (strengthened)

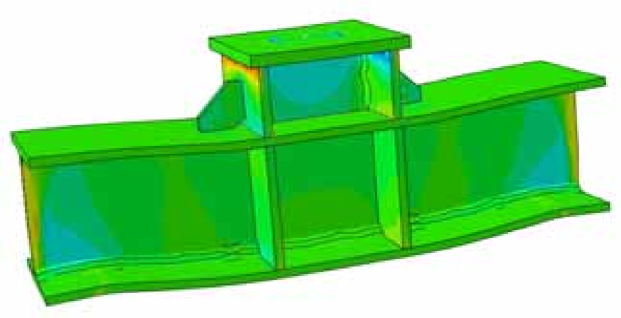

Fig.20 Stress Syy (initial)

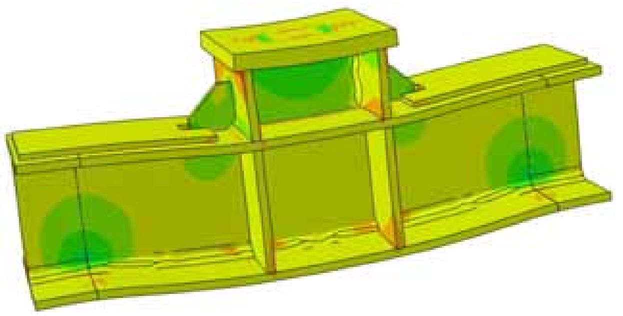

Fig.21 Stress Syy (strengthened)

Fig.20 has to be compared to Fig. 21 in order to see how stresses developed in these two situation. A better understanding may be described in Fig. 22 and Fig 23 where the ratio between stresses on the pressure surface, support surfaces and stresses in the elements is higher in the strengthened specimen.

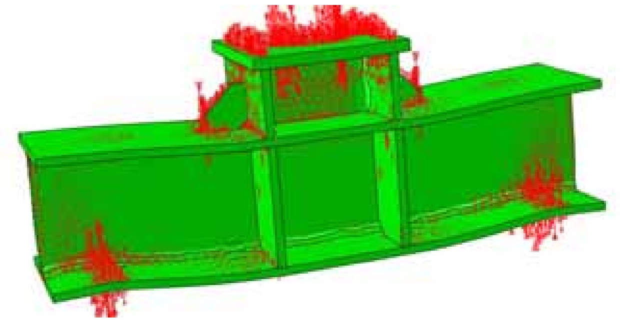

Fig.22 Stress Syy (initial)

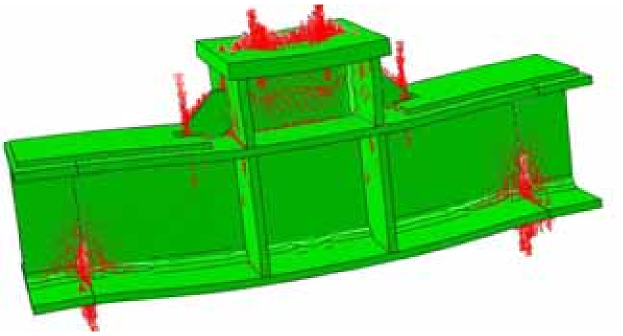

Fig.23 Stress Syy (strengthened)

Fig. 24 has to be compared to Fig. 25 and Fig. 26 to Fig. 27 where the same difference in stress ratio is presented.

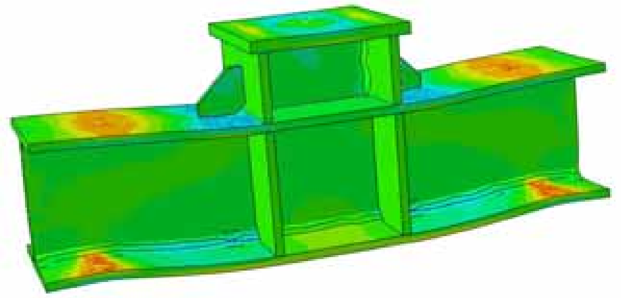

Fig.24 Stress Sxx (initial)

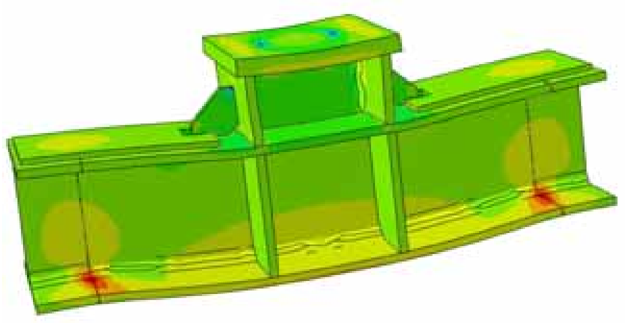

Fig.25 Stress Sxx (strengthened)

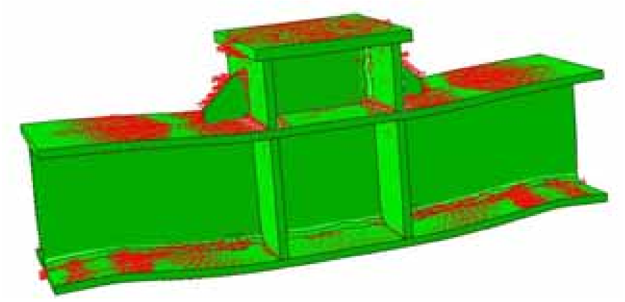

Fig.26 Stress Sxx (initial)

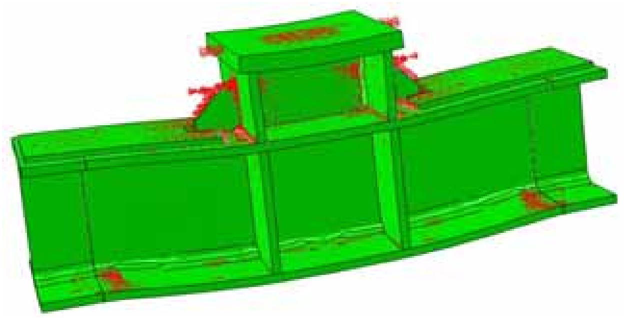

Fig.27 Stress Sxx (strengthened)

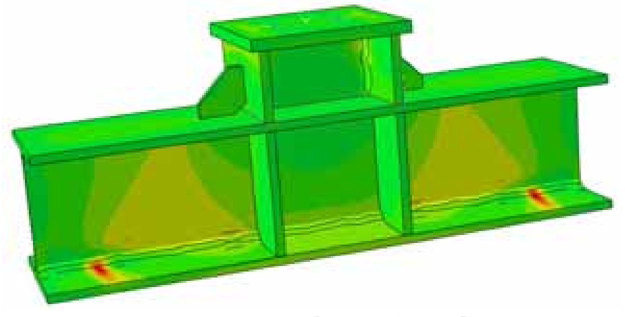

Fig.28 Stress Principal Max (initial) step 10

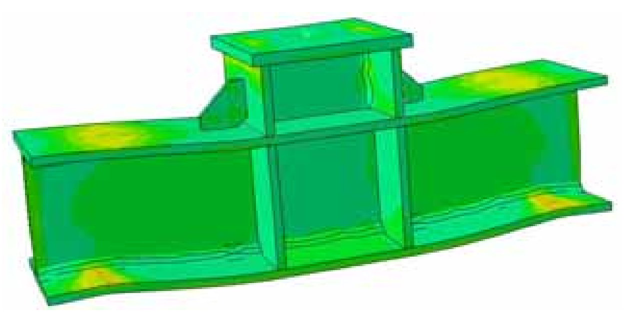

Fig.29 Stress Principal Max (initial) step 20

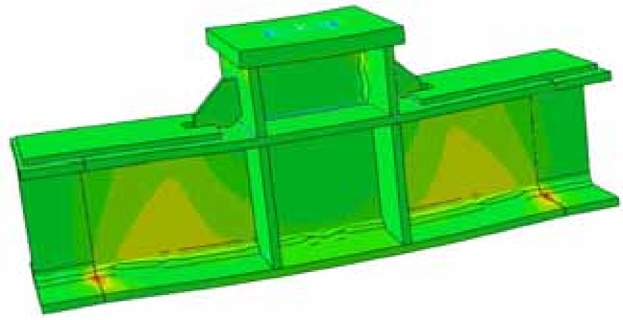

Fig.30 Stress Principal Max (strengthened) step 10

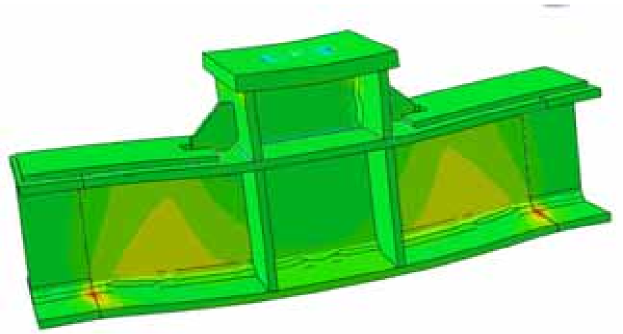

Fig.31 Stress Principal Max (strengthened) step 20

It can be noticed, in Fig. 28, to Fig.35 that the strengthened specimen does not differ very much from 1000kN to 2000kN. (the figures look almost the same because the distribution is the same but the values are proportional to the applied load).

The panel between the stiffeners of the column does not have an obvious shear behavior and the values of the stresses in principal direction have, almost, the same values as for the vertical direction

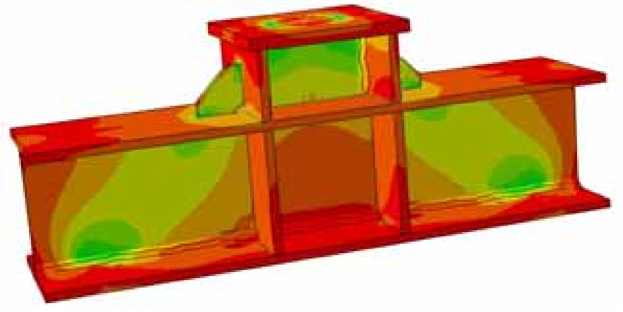

Fig.32 Stress Principal Min (initial) step 10

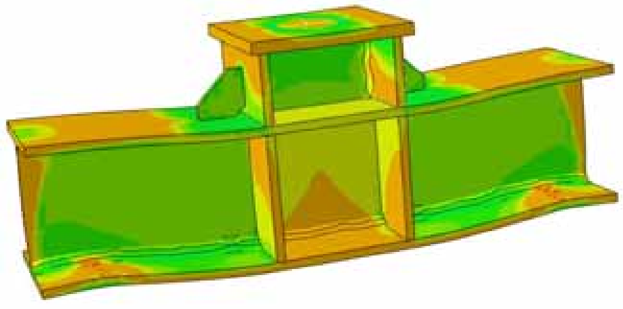

Fig.33 Stress Principal Min (initial) step 20

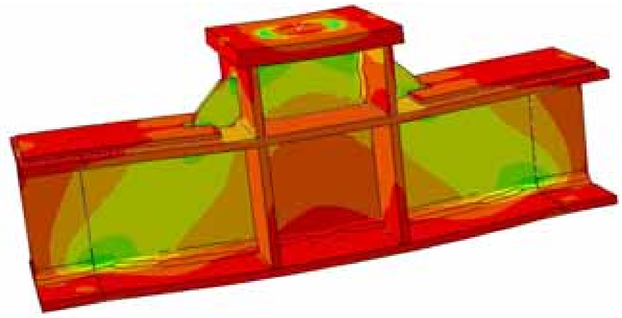

Fig.34 Stress Principal Min (strengthened) step 10

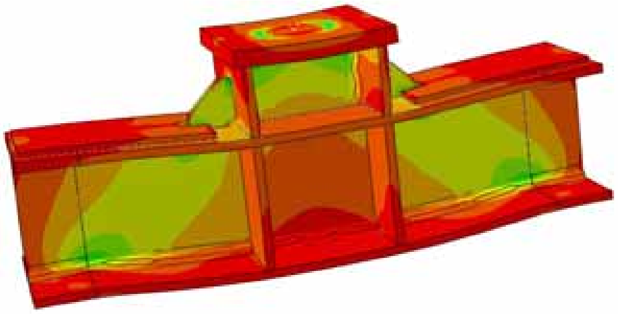

Fig.35 Stress Principal Min (strengthened) step 20

Fig.36 Print of pressure cylinder (test)

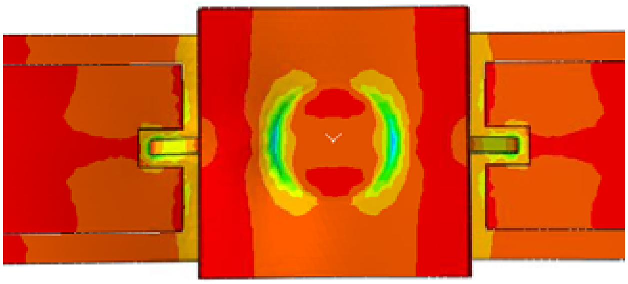

Fig.37 Print of pressure cylinder (FEA)

The last two figures, Fig. 36 and Fig. 37 present the imprint of the pressure cylinder in the experimental test and in the finite element analysis. Although both cases started with a circle as pressure surface, because of bending and deformation there has appeared two surfaces which relate very closely to the real situations. This was possible by defining a contact definition between a cylinder and the specimen. The force defined in a point does not give accurate results.

6 Conclusion

The repair and strengthening of steel structures have become increasingly important in civil engineering tasks. The steel structures are durable, they do deteriorate significantly over time and to extend their service life, they must be repaired. Repair measures enable the deteriorated steel structures once again to sustain the action defined in their original designs. Strengthening allows the designed actions to be increased. Both types of measures should be fully exploared before demolition and/or replacement by new structure.

The results for this finite element analysis were very close to the results in laboratory. This is very important to know since, for the future, the need of experimental tests will be smaller, for certain modifications in the features of a steel frame connection.

The finite element analysis shows the deformed shape of the connection and can give a more accurate location of the affected zones. Results show that, although there is a rigidity loop on the column, the stresses do not exceed the yielding point in that area. This doesn’t mean that the connection is well designed since the over-strength coefficient has to be taken into account when a design for seismic action is performed.

Another idea resulted from this analysis, is the one that attention should be directed to other effects of the action. Here, although the stresses in the flanges decreased, the stresses in the web of the column increased, for the same acting force.

Finite element modeling enables strengthening solution optimization for welded frames in order to reduce the stress in critical points based on strain and stress solutions. Validation of strengthening solutions of welded joint obtained by finite element modeling was done experimentally by electrical resistive tensometry method. Tensometry measurements results were correlated with finite element modeling results.

This paper has analyzed the behavior of a frame connection in different constructive variants, which were tested in the laboratory. Analyzing the obtained results for the principal stresses, von Mises stresses and stresses after x, and y directions, it was found that a better behavior has developed.

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