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Measuring Strain in Sheet Metals

A sensitive and precise experimental system able to time-track the static and dynamic response of steel sheets to intense loads is hereby described. This methodological article is based on a specific investigation carried out in order to verify the correct functioning and safety conditions of a large sheet metal structure. Several suggestions and practical tricks are presented in ample details describing in what ways they allow to improve the results of the experiment.

Keywords: *experimental mechanics; testing procedures; strain measure; strain gauges; stress evaluation; steel sheets; loading systerms; telescopic boom*

1. INTRODUCTION

Theoretical calculations and numerical modelling are complementary aspects and indispensable tools with the scope to use sheet metal for structural functions safely [1-4].

On one side, theory is able to propose quick explanations and solutions, generally valid for a large spectrum of simplified and mildly simplified problems [5, 6]. On the other side, numerical calculations, mainly performed by Finite Element Methods (FEM) [7] or meshless methods [8, 9], permit to investigate situations that are not far from reality in terms of complexity of systems and/or physical occurrences [10-14].

However, the complication of the real phenomena at stake is recurrently such that it gives designers doubts that only experimental tests can dispel [15, 16].

Specific electrical sensors, called strain gages, are commonly used to estimate the deformation and, then, the level of stress locally reached by metal sheets in the positions of great interest [17,18]. In particular, among the various solutions available on the market, electrical resistance variation strain gauges are used for the numerous advantages they offer, like the possibility to be placed on surfaces with any spatial orientation [19] with the aim at monitoring the sheet deformation and its anisotropy [20], both in elastic and plastic regimes [21], respect to the different load conditions. When properly installed and protected with a suitable layer of silicone, they can work in damp and dusty or, even, humid, environments, remaining operative also in the case of protracted testing campaigns [22].

Deformations are detected by strain gauges measuring the electrical resistance on a conductor in consideration to the fact that it is proportional to the length and dimensions of the section by means of a resistivity value. By dilating the conductor, for example in an axial direction, the length of the conductor grows and the section is contracted.

Considering the resistivity substantially independent of the dilatation, it is possible to obtain a conductor showing a resistance variation proportional to the mechanical dilatation by electrotechnical calculations. The coefficient of proportionality, called extensimeter factor (or *gage factor*), has a value that could be theoretically obtained taking into account the material used and its properties. But, since the real value is even 60% far from this theoretical evaluation, experiments are used for its correct definition.

The strain gauges are made by photoengraving starting from an extremely thin conductive alloy sheet embedded in a thin film of plastic as support material (generally polyamide), which also has the task to electrically isolate the strain gauge from the mechanical component placed under test. The dimensions of the metal grid are kept to a few millimeters to ensure localized and precise dimensions and, consequently, very localized measurements. The grid is made of constantan (45Ni, 55Cu), a material able to guarantee that the proportionality factor remains linear in a wide deformation field, even under plastic deformation, showing negligible hysteresis phenomena, thermal stability and, finally, a high specific resistance (in order of 0.5 μΩm) to improve its sensitivity.

In other terms, strain gauges, and also the different measurement systems that can be realized by these sensors, appear to be simple, economical and enough precise, lending themselves particularly appropriate to 'do-it-yourself' measurements. At the same time, without a suitable prior experience, including a practical ability toward the correct use of these sensors and signal acquisition devices, measurements can be subject to errors, as well as the entire experiment.

2. AIM AND SCOPE

The present article details an example of a sensitive and accurate experimental system, based on strain gages use, and able to monitor both the static and dynamic responses of the steel sheets in the case of intense loads. All technical

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solutions and practical tricks implemented during a previous specific experiment [23-27], in which a large sheet metal structure represents a telescopic boom characterized by great complexity and dimensions, are presented.

The test has been carried out in order to verify the operational safety and functionality of this equipment in extreme load conditions [23]. At the same time, it is noteworthy that this connecting system has been largely analysed in the past both at the level of theory [28,29] and numerical models [30]. In addition, several interesting experiments deal with the behaviour of thin metallic walls in similar load/boundary conditions [31-33]. As a direct consequence of these considerations, the present article has not been implemented with the scope to continue to analyse the behaviour of a telescopic cantilever beam. Instead, it finds the opportunity of the experiment on the telescopic boom, already discussed in [23, 31], as a way to investigate the procedures to be adopted for a correct implementation of the experiments [34,35]. As results, numerous practical details and some good tips explain how to apply and use the sensors, suggesting how to pay particular attention not to incur the most common measurement errors.

3. EXPERIMENTAL SET-UP

Strain gauges must be glued carefully to the workpiece surfaces to make a single body and not slip during their deformation and, consequently, cannot be recovered after the test. The adhesive material must have the minimum possible thickness so that the strain gauge is very close (and integral) to the contact surface ensuring the correspondence between the detected and real expansions. After gluing, for which in our case a special cyanoacrylic adhesive was used, it is necessary to wait for the glue to dry, make the electrical connections and then apply a layer of silicone to protect the strain gauge from moisture and dirt. Further details are presented regarding the actions necessary for a correct fixing of the strain gages.

1) Coarse cleaning of the application areas: this operation is necessary when the steel sheets have oxide layers (Figure 1) that could interfere with the correctness of the detection. During cleaning, care must be taken not to deteriorate the surface too much to prevent grooves or depressions from making an unprecise deformation measurement. In the present case (Figure 2), the operator had to take particular care to keep the rotating abrasive disc (with a diameter of 100 mm) perfectly equal to the surface.

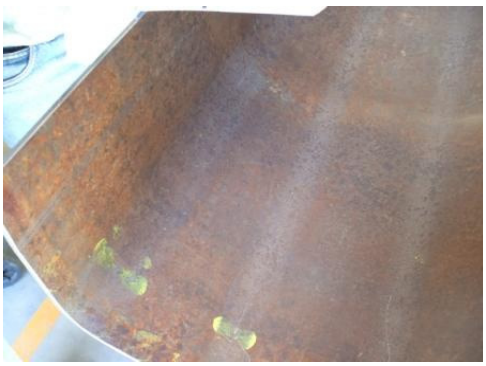

Figure 1. Cleaning the area of application of strain gages from metal oxides is the first step.

Figure 2. Prevent the abrasive disc from leaving furrows or depressions.

2) Localization of the reference axes: this phase is perhaps the most delicate due to the difficulty in precisely identifying the point of application and the orientation of the strain gauge (Figure 3). Once recognized, the axes can be traced and highlighted (Figure 4) providing support lines for subsequent positioning and correct orientation of the unidirectional strain gauge.

Figure 3: Highlight the geometric lines to help in the correct positioning of the strain gages.

Figure 4: Find the exact point where the strain gauges should be located.

3) Smoothing of the application areas: it is important now that the area on which the strain gauge is applied has a very low roughness so that the surfaces of the sensor and of the piece are very close and integral with each other. It is possible to get well-polished surfaces by passing the sandpaper first according to a bisector of the plotted axes (-45°, as in Figure 5) and then in the orthogonal direction to it (+45°, as in Figure 6). For this

manual operation, three different grains of finer-grained sandpaper were used in sequence, starting with a coarse P120 and moving to a P280 medium paper and a very fine P400.

Figure 5: Sand the surface with grit sandpaper.

Figure 6: By making passes with orthogonal directions, super smooth surfaces are obtained.

Figure 7: Degrease the area with a swab dipped in alcohol.

Figure 8: Always cross the passes to get a better cleaning.

4) Degreasing and cleaning of the area: the perfect cleaning of the surface is the fundamental prerequisite for a strong bonding. In fact, metal dust is certainly present in the area concerned and then removed with the previous smoothing operation, in addition to the thin layer of oil that is usually present everywhere in the mechanical workshops. Using a tweezers, take a cotton wool pad and wipe it with isopropyl alcohol, then pass it on the surface, rotating it so as to always offer a clean part of the pad (Figure 7). You should always cross the passes at +45° and -45° as for the sandpaper and in the final one, use two clean swabs in rapid succession: first you pass the wet one and immediately after the dry one (Figure 8). The cleaning operation must be repeated until the cotton remains white after the past, proving the attainment of a good result.

5) Positioning of the strain gauge: once removed from its hermetic packaging, the strain gauge is placed upside down on a piece of adhesive tape, also overturned, so that it can be easily maneuvered even in the following phases (Figure 9). Then it is lifted and positioned on the surface of the piece respecting the coincidence between the axial and transverse references present on it and the tracking lines (Figure 10). The adhesive tape now holds the strain gauge on the piece. It is necessary pay attention to always use tweezers to handle the strain gauge and never take it in hands to avoid dirt contamination.

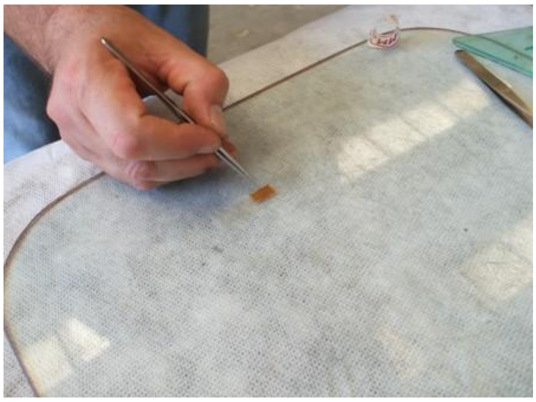

Figure 9: Remove the strain gauge from the package and place it upside down on a strip of adhesive tape.

Figure 10: Overturn the adhesive tape, being careful to position it correctly on the sheet.

6) Fixing the strain gauge by gluing: a strip of adhesive tape (and consequently also the strain gauge) is raised, then place on the piece a fair amount of glue (Figure 11) and lower the flap slowly checking that the

references return to coincide, and beginning to compress the extensometer with the thumb (Figure 12). To avoid the risk of sticking the finger, a teflon square is interposed and the pressure must be applied for at least one minute (Figure 13). This is the time necessary for the glue drying reaction to take place, after which the sensor is perfectly fixed (Figure 14).

Figure 11: Lift the adhesive tape with the extensor and place the glue on the sheet surface.

Figure 12: On the right: lower the tape again and compress the strain gauge on the sheet with a finger.

Figure 13: Interpose a little square to avoid direct contact between glue and hands.

7) Elimination of excess glue: since the glue comes out not only from the area of the strain gauge, but also from that of the adhesive tape, it is necessary to scrape it with a blade (Figure 15) and finish the work with sandpaper (Figure 16). This work around the strain gauge does not have an aesthetic purpose, but is essential to ensure that the silicone that will subsequently be applied adheres well to the surface preventing moisture from entering and damaging the glue.

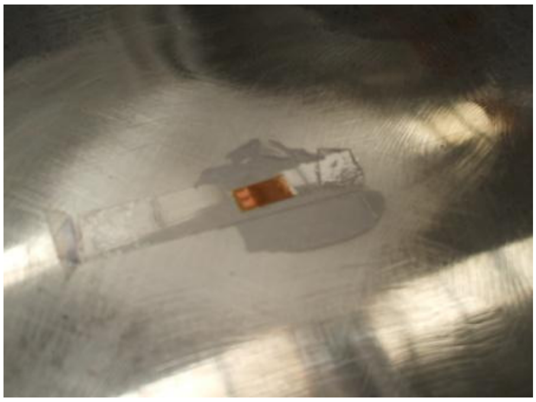

Figure 14: Right: continue to press for the time necessary to solidify the glue and lower the strain gauge.

Figure 15: Scrape excess glue with a razor blade.

8) Connection of electric wires for tinning: after raising the temperature of the stagnator (Figure 17) up to a value that depends on the capacity of the structure to absorb and dissipate the heat (approximately 400°C in the present case), the wires are welded to the strainers of the strain gauge (Figure 18). The cables can then be collected in flexible sheaths to protect them from high temperatures, dust and humidity.

Figure 16: Complete the surface cleaning with sandpaper.

9) Signal test: through a tester the resistances of the various connections are now checked (Figure 19). This control is fundamental because it signals any current leakage between the strain gauge and the piece, but also highlights if the cables have short-circuit effects. Furthermore, this test is an opportunity to verify that the resistance of the sensors and cables coincide with the nominal ones supplied by the manufacturers. At this

point, through an acquisition unit (in our case, the model P-3500), placing the amplification at zero and the gage factor equal to 2.095 (specific value indicated by the manufacturer), we obtain the gross balance values and ends for a 1/4 Wheatstone bridge connection with strain gauge not deformed (Figure 20). These values are mainly used to check and cancel any residual stresses due to welding or assembly of the sheets, especially if the strain gauges have been installed before assembling.

Figure 17: Bring the soldering iron to the appropriate temperature.

Figure 18: Solder the signal cables to the strainers of the strain gauge.

10) Laying of the silicone: once the electrical connections have been checked, a layer (Figure 21) of a silicone layer (in our case DOW CORNING 3145 RTV MIL-A-46146) is applied to protect the strain gages both in the eventual last assembly phases and during the experimental campaigns. An important precaution is to crush the edges of the silicone well (Figure 22) so the humidity does not creep under it. At this point, the area must be left to ensure complete drying and solidification.

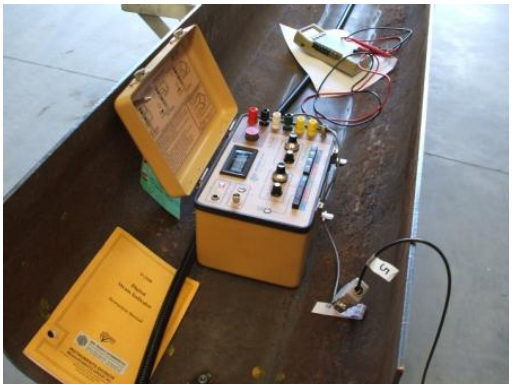

Figure 19: Check the resistance in the various connections by means of a tester.

Figure 20: Connect the cables to the control unit and acquire the balancing values.

Figure 21: Apply a layer of silicone to protect the strain gauge.

Figure 22: Squeeze the edges of the silicone firmly to isolate the contact area.

4. PLACEMENT OF STRAIN GAGES

The minimum number of strain gauges necessary to monitor the sheets with efficiency depends on the dimensions, on the complexity of the geometries, on the loading level and constraint conditions to which the structure is subjected. Another important practical limit is linked to the characteristics of the control unit(s) available and to the number of channels that can be acquired simultaneously. In the case described here, during the tests 15 strain gauges were read by 3 acquisition units and synchronized through the same clock signal.

The first strain gauges (in our case the numbers 1, 2, 3, 4) are usually positioned so as to be the most significant to understand the behavior of the structure and are used to analyze areas of stress concentration and greater criticality. Sometimes, these sensors are located in places that are not easily accessible, close to covering areas that are not clearly visible during the tests. Precisely for these strain gauges it becomes particularly important to frequently check the correct functioning (e.g. slipping between the sheets, sudden bending of the surfaces may deteriorate the sensor or the glue): the quality of the measurement can be checked by ensuring that the measurement of the value of zero (i.e. the reading of the strain gauges at zero load) remains constant as long as the plates do not undergo plastic deformations.

When using (as in the case described) monodimensional strain gages, able to acquire the deformations only along one direction, for each point of interest it is advisable to insert two strain gauges orthogonally oriented to each other (Figures 23, 24, 25) so as to observe the whole deformation state.

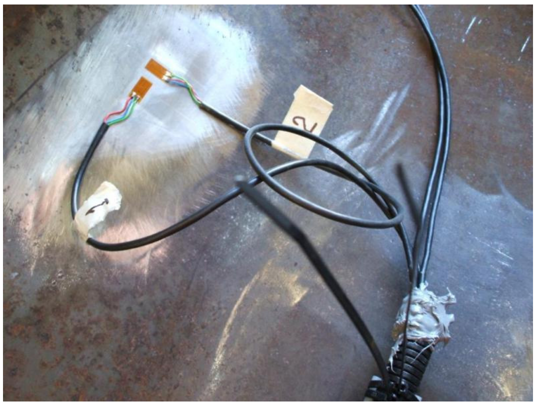

Figure 23: Place more than one strain gauge in the same area to ascertain the stress state.

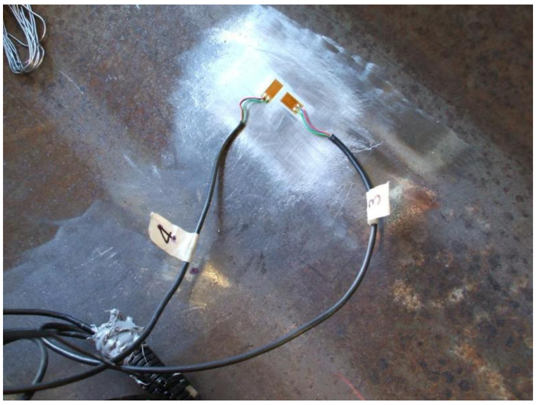

Figure 24: Repeat the placement of additional strain gauges in all areas of interest.

If the zone is subjected to a monoaxial state of tension (a situation that only occurs far from the contact and covering areas), the strain gauges placed transversely to the main voltage direction must measure values of the order of ν times (with ν Poisson coefficient of the material) with respect to those on the main direction. Each difference in this ratio indicates the presence of phenomena that move the zone away from a stress state of a membranous type, like in torsion effects of the laminates due to loads or asymmetric constraints.

More generally, the various classical theories available on the mechanics of materials such as De Saint Venant's [5], should provide a useful support to verify the functioning of the experimental system and the validity of the measures, especially observing those areas far from the peaks of stress concentrations.

In particular, in the presence of nominally symmetrical loads and constraints, some strain gauges could also be intentionally placed symmetrically on the sheets, so that by comparison of their measurements, unexpected effects could be detected like torsions of the structure for non-symmetrical loads/constrains.

Localized effects, such as those close to the contact areas, can be better interpreted with strain gauges placed very close to each other (as, for example, in our case for strain gages 5 and 6, respectively, glued on the inner and outer surface of the sheet as per Figures 25 and 26).

Figure 25: Cure the position of the strain gages so as to be able to detect the deformation state over the entire area.

Figure 26: Install the strain gauges both inside and outside the sheet to compare the readings.

Sometimes, it is better to place additional strain gauges in strategically selected areas to prevent unexpected or unwanted effects, such as buckling of parts of the structure.

These "guardians", to be really useful, should be placed in areas where no strange indications are expected (e.g. areas with low deformations or that should not deviate from simplification theories) or very close to other strain gages whose measurements can be used as basis of comparison.

At the same time, the chosen zones should be such that, in an unexpected event, show a deformation behavior markedly different from the rest of the structure. This is the case, for example, of the strain gauge 15, positioned near the strain gauges (internal) 1 and 3, but on the outer surface, with the task of signalling the local instabilities of the sheet. A final caution is to install, in the most critical areas, a larger number of strain gauges than strictly necessary (in our case the numbers 7 - 10 as shown in Figure 27). In this way, the experimental sessions can be continued by simply replacing the electrical cables from which the signal can be detected in the case of sensor malfunctioning related to the deterioration of gluing, for instance.

Figure 27: Provide strain gages placed in stand-by that intervene in case of malfunction of those in line.

Figure 28: Monitor the plates so as to immediately highlight instability effects.

5. LOADING SYSTEM

The loading system depends on the test conditions of interest and the load values to be achieved. Below is an example of a hydraulic circuit (Figure 29) consisting of:

1) Electric motor connected to the main pump.
2) Oil tank.
3) Analogue pressure gauges to evaluate the pressure in each jack (full scale at 300 bar).
4) Two manually operated three-way valves to regulate the flow of oil into the jacks.
5) Mechanical valve that manages the difference in pressure between the jacks.
6) Maximum valve on the cylinder duct which is at the top pressure.
7) Maximum valve that protects the entire system.
8) Flow control valve.
9) Hand pump to accurately reach the desired pressure (fine measurement).

and connected to the two jacks (Figure 30).

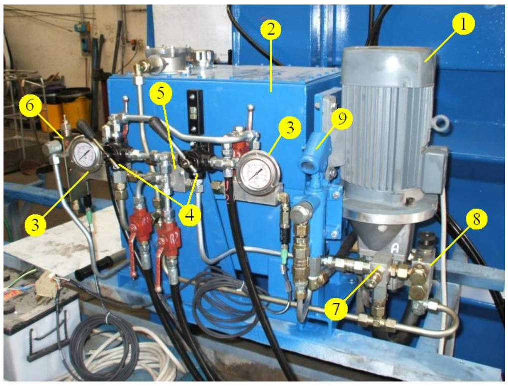

Figure 29: Create a loading system, hydraulic or electric, that guarantees compliance with the test conditions.

During the loading phase, the operator could use a digital pressure gauge (Figure 31) which is more accurate than the analogic ones installed on the system, also having the additional function of controlling the temperature of the circulating fluid.

Through special loading conditions it has been possible to load the structural sheet system both with a pure bending moment and with a moment plus a cut.

The acquisition of the pressures acting in the jacks has allowed to derive the value of the forces transmitted to the model. Naturally, this is a measure that is a bit imprecise because it contains all the phenomena of hysteresis due to the reorganization of the mechanical system of the hydraulic circuit. In addition, the hydraulic system is likely to be inaccurate in the discharge phase (whose accurate study could affect).

Figure 30: Dimension the loading system so as to leave a wide margin of use during the experimental phase.

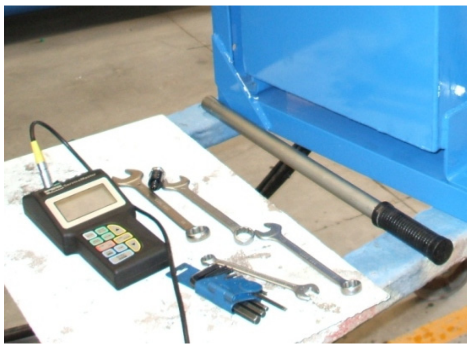

Figure 31: Instruments and simple tools at disposal.

6. ACQUISITION SYSTEM

The ambition to measure a large number of deformations has led to the need to acquire many signals in a contemporary way using different synchronized instruments (Figure 32).

For the first 8 strain gauges, the portable Esam Traveler system was used (Figure 33a), while, for reading the pressure in the two hydraulic jacks and the signals of 2 other strain gauges, a National Instruments DAQ USB system combined with two Vishay analogue control units model P-3500. For another 3 strain gauges it was necessary to use a further Vishay control unit, of the digital type (Figure 33b), with USB connection.

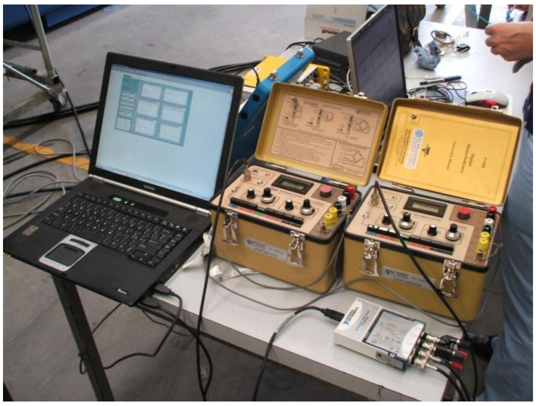

Figure 32: Switch to signal acquisition and data processing.

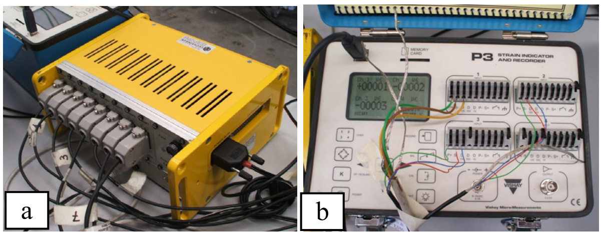

Figure 33: Electronic devices used during the experiment: a) the portable Esam Traveler system; b) National Instruments DAQ USB system combined with two Vishay analogue control units model P-3500.

7. CALIBRATION OF THE EXPERIMENTAL SYSTEM

Before carrying out any experimental session, the system has to be calibrated. In particular, the pressure sensors were calibrated using an external measuring device, also verifying that their response remains proportional to the pressure rise. Then, the calibration of the strain gauge system was carried out, acquiring the values read in the absence of external loads, but with sheets subjected to its own weight. A few intense load cycles can be used to make the system settle and with the acquired values the strain gauges have been nulled. The system is now ready for acquisitions.

8. MEASURES

In particular, the acquisition procedure was validated on a double hinge beam configuration [28]. In Figure 34, scheme of forces and constrains is shown, together with the diagrams of shear force (T) and bending moment (M_f). Forces are supplied by two hydraulic pistons whose pressures are raised rather slowly during tests and in a balanced manner. In this way, the configuration permits to provide, by two forces (F_1 and F_2) opposite as direction, but almost equal in modules, relevant bending moments with negligible shear forces in quasi-static conditions.

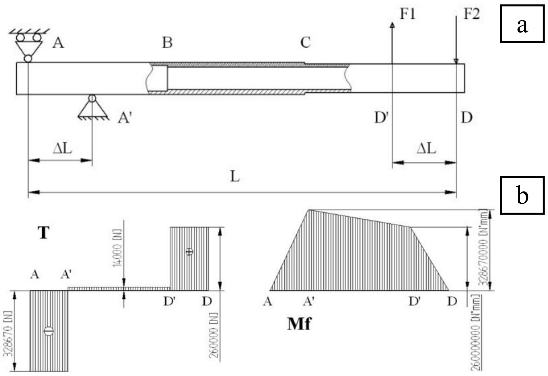

Fig. 34. Scheme of forces and constrains (a); diagram of shear force (T) and bending moment (M_f) (b) [25].

Strain gauges deliver measures on local strains in terms of micro deformations to be filtered and analysed. In Figure 35 is reported an example of the kind of information available from tests thanks to the use of strain gauges. In particular, Figure 35a exhibitions the trends of local strains, measured in 4 different locations by 4 strain-gauges, respect to an increase of loads in time. In Figure 35b, the time-dependence is removed, showing the ratio between strains vs force.

A great selection of information becomes available thanks to the interpretation of the experimental data. For instance, Figure 35a immediately shows which is the most stressed zones in the structure and the related stress values, but it also gives information regarding the conditions of stress (as tension or compression, and direction). In addition, Figure 35b, reporting the values of strain in a load/unload cycle, is able to clearly show a hysteresis effects in the mechanical structures.

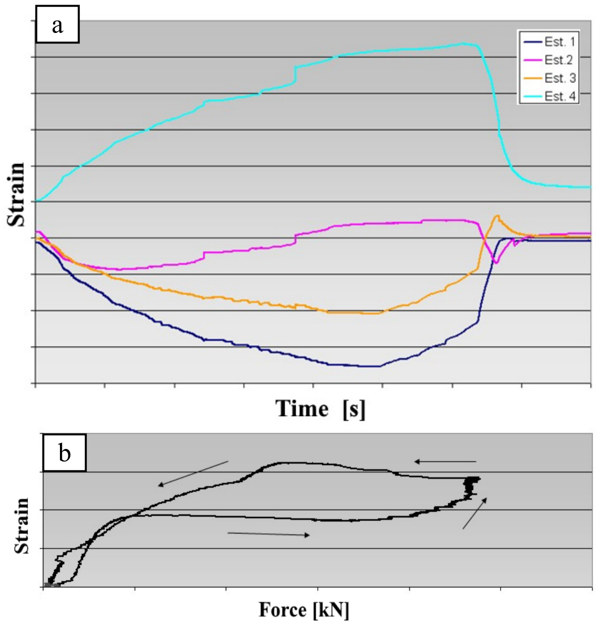

Fig. 35. Information measured from tests by strain gauges, expressed as strains vs time (a) or strains vs force (b) [22].

9. CONCLUSION

Sheet metal is transformed by an industrial process into flat and thin pieces. These semifinished pieces, available on the market in a wide assortment of dimension and thicknesses, permit the quick and cheap fabrication of everyday objects. At the same time, the needs of the designers, continually aimed at reducing the amount of material and the costs of the structures, push towards lighter and thinner sheets. But this tendency often goes to the detriment of security. Theoretical calculations and FEM tools offer a great help allowing to evaluate a priori the maximum stresses and deformations of the structures in order to verify if the latter fall within acceptable limits. At the same time, it often happens that apparently secondary effects such as the instability phenomena of buckling can arise in a completely unexpected and difficult to predict by numerical and theoretical considerations. For this reason, experimental tests, especially in the presence of thin sheets, continue to be a necessity. In this article, based on a previous experimental investigation [23-28], a quick and simple method was described to measure the deformations of slender metallic structures in static and dynamic conditions through strain gauges. In particular, we have described all the operational steps that have led to guaranteeing good quality in measurements through specific adjustments and technical solutions.

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МЕРЕЊЕ НАПРЕЗАЊА У ЛИМОВИМА

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Осетљив и прецизан експериментални систем који може да прати статички и динамички одзив челичних лимова на интензивна оптерећења је описан. Овај чланак се заснива на специфичном истраживању које се спроводи у циљу провере исправног функционисања и безбедносних услова великих лимених структура. Неколико сугестија и практичних трикова је представљено у детаљима који описују на који начин допуштају побољшање резултата експеримента.