ERROR ANALYSIS OF PIPES SUBJECTED TO INTERNAL PRESSURE USING THE ISHIKAWA DIAGRAM

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Abstract. *The use of steel pipelines in industries is generalized and adopted worldwide. In order to optimize the design and the use of these components, there are experiments that are being carried out and the identification of sources of errors is an important issue. Many techniques can be adopted to determine and control a list of causes of errors. In this work, the Diagram cause-effect of Ishikawa and the Method of 5M, will be used in an experiment with low carbon steel pipes, closed with flat ends at both extremities and subjected to hydrostatic internal pressure. The specimens were machined in the central region, to simulate a defect (i.e. thickness loss) and repaired with a carbon/epoxy composite.*

***Keywords**: Ishikawa Diagram, error source, steel, pipes, experimental analysis, composite material*

1. INTRODUCTION

Nowadays, the use of steel pipes in many industrial sectors is extensive worldwide (Telles, 1997). However, steel pipes have surface problems due to corrosion originated by external vapors, gases pollution and humidity in general. In addition these components can be subjected to extreme internal hydrostatic pressure. Thus, it is important to develop scientific and experimental research with industrial pipes, to determine their properties, characteristics and mechanical behavior. In order to optimize the design and the use of these pipes, there are tests that are being carried through in many sectors of engineering.

However, any experimental technique and practical procedure is associated with errors of measurement. These errors can modify results, so they have to be studied. And, more important than calculate the associated total error, is to identify the sources of these errors, in order to minimize or eliminate them.

In this way, many techniques can be used to determine and control a list of causes of errors. In this work, the Ishikawa Diagram will be used, through the Method of 5M. This method leads to all the causes of the experiment errors, including Human, Methodology, Machines and Materials, Management and Environment. In order to demonstrate the methodology of application of the Ishikawa Diagram in the analysis of a practical procedure, this work will consist of analysis of the errors associated to an experiment of great importance and high technological value for the industrial, for the preventive and maintenance sectors and for companies who carry through emergency repairs of the pipes. In this work the use of the Ishikawa Diagram will be exemplified with a pipe that needs a fast repair to avoid its burst.

In this direction, the experimental materials and equipments, procedures and sources of errors will be detailed, in some experiments with steel pipes of low carbon that had been machined in the central region (to simulate a defect) and had been repaired with composite material (epoxy resin with glass and carbon fibers).

A theoretical model concerned with the mechanical behavior of pipelines reinforced with advanced composites, including analytical equations for stress analysis, was presented by Toutanji and Dempsey (2001). Few years later, Levy-Neto et al. (2005) presented some experimental and numerical results about the elastic behavior of aluminum pipes repaired with carbon/epoxy layers. And, as far as the experimental and numerical prediction of the maximum internal pressure that a steel pipe repaired with hybrid composites is concerned, the work of Felippes et al. (2007) presents some new results. It was detected in these previous studies that this kind of repair was one of the most efficient.

Thus, experiments with the mechanical behavior of pipes, which have covers in their extremities and are submitted by internal hydrostatic pressures, will be analyzed by using the Method of 5M.

2. METODOLOGY AND GENERAL SCOPE OF THE ANALYSIS

In the experimental analysis, including the linear elastic as well as the burst behavior, the mechanical response of steel pipes was verified. Both, theirs ultimate pressures, as well as the longitudinal positions where the failures occur, were estimated. These results are very important for industries that need to select the type of repair that will have to use in their damaged pipes. To carry through this kind of experimental and to get the desired results, it had been analyzed, in a test rig in the SG-9 Laboratory (University of Brasilia), the behavior of three kinds of steel pipes: (i) perfect pipe (with constant thickness); (ii) damaged pipe (machined pipe in the central region, see Fig. 1); and (iii) repaired pipe (machined pipe in the central region, which was repaired with composite material, see Fig. 2).

The test conditions and the basic specifications to carry then out followed the ASTM A-53 standard, for general use (Telles, 1997). The perfect pipe will be considered as the ideal condition, since it represents original pipe that had not suffered any type of problem.

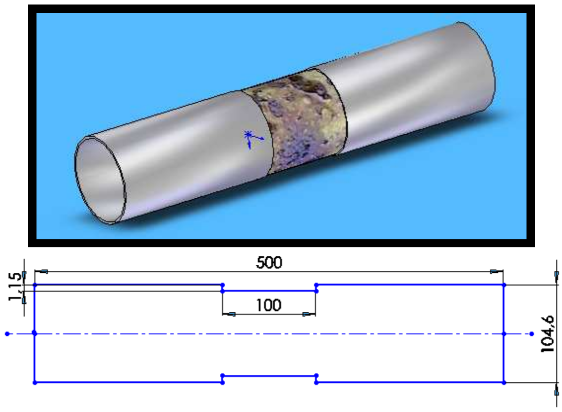

Figure 1. Problematic Pipe.

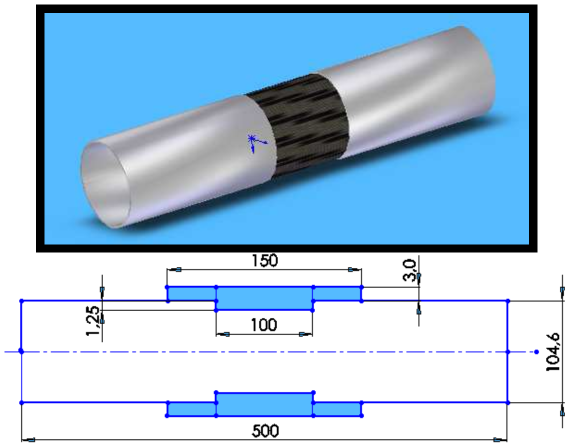

Figure 2. Repaired Pipe.

3. MATERIALS AND EQUIPMENTS

The main specimens, all with nominal wall thickness of 2.5 mm were designated as: Tube 1 (for the perfect pipe); Tube 2 (for the damaged pipe, see Fig. 1) and Tube 3 (for the repaired pipe, see Fig. 2). The pipes investigated in this study are made of steel, SAE 1010, 500 mm long, with nominal diameter of 100 mm and welded along the longitudinal direction. All tubes (presented in Fig. 3) were clamped in the left extremity and closed with flat ends in the right one, having 10 equidistant screws in the flanges, which were fixed with TIG welding. More information about the specimens can be seen in Table 1.

Table 1: Pipes used.

TUBE 1	Perfect pipe, without barbs, covered in the two extremities.
TUBE 2	Pipe roughed-hew mechanically in the central region (length of the machined region = 100 mm and depth of the machined region = 1.15 mm), without barbs, covered in the two extremities.
TUBE 3	Pipe roughed-hew mechanically in the central region (length of the machined region = 100 mm and depth of the machined region = 1.25 mm) and repaired in the same central region with composite material, without barbs, covered in the two extremities.

Figure 3. Three specimens used.

The glass and carbon fiber fabrics used were balanced, with a volumetric fraction of 50% and a thickness of 0.25 mm and 0.50 mm, respectively. The resin epoxy was a modified Araldite LY 1316 BR (Huntsman, 2005), while the catalyser used to speed up its cure was HY 1208.

The equipment of data acquisition is an ADS 2000, with 16 canals, connected to a microcomputer, that carries through the tasks of gauging of data, compensation of temperature, balancing of electrical resistances and reading of the measures of axial and circumferential deformation, with precision of $0.1x10^{-6}$ (Faluhelyi, 2006). The procedures of use of the equipment are enumerated:

• Bind the handles of the strain gauges circumferential and axial in canals 0 and 1, 2 and 3, respectively;

• Calibrate the system of acquisition of data by means of the analogical entrance of signals, with the value of engineering in the system of acquisition of data that depends on the value of the measure of deformation, of the electrical resistance of the calibration, superior and inferior excitement of the strain gauges with 2.5 V and limits of the scale more or less not to saturate the difference of 10 potential of V (that it is regulated by the entrance that can go up to 5000, in the system of the Lynx mark);

• Connect canal 5 to the pressure transducer, to monitor the pressure during the test;

• Wait the system to stabilize (until values of calibration approximately to remain constant); and

• Record the data for the necessary amount of time to the experiment.

The test rig is composed of a metallic steel box 1020, with thickness of 3 mm, 1200 mm of length, 300 mm of width and 400 mm of height, with two columns, fixed in the base of the box. One of its functions is to support the extremities of the pipe and allow that they have the same axial displacement during the experiments. For measure of security, this test rig prevents any accident with the operators. The cover of the metallic box is of acrylic, with 5 mm of thickness, that resists the impact of any part of the projected pipe or oil in the direction of the acrylic cover, being transparent to allow the visualization of the pipe in the experiment (Fig. 4).

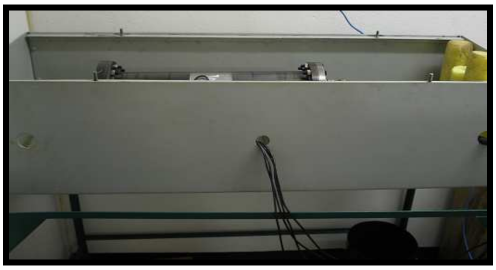

Figure 4. Test Rig.

The Enerpac hydraulic pump has power of ½ HP, and capacity of 70 MPa (700 bar), so it has capacity to carry through the tests. The oil of the used compressor is MS Lub Schulz, being very used as lubrificant for alternative air compressors.

The hydraulic pump and the body of test are connected by means of a steel hose, with capacity of pressure up to 30 MPa (300 bar). It is used to carry the oil from the pump to the pipe and is installed through copper connections in the entrance of the pipe and the exit of the pump, that resists until the same capacity of the hose. The pressure transducer, with band of operation between 0 and 40 MPa, monitors the pressure during the whole test and receives an excitation of 24 Volts.

4. ISHIKAWA DIAGRAM ANALYSIS

Different techniques can be used to facilitate the determination of causes of errors. In this work, the cause-effect diagram will be used, with grouping in families, according to Method of 5M, which leads to the attainment of a list of all the causes of errors and includes: Man power, Methods, Machines and Materials, Management and Environment. This tool of analysis, also known as "diagramme d' Ishikawa", allows a schematical form to visualize the relations between effect and causes in an experiment, as presented in Figure 5.

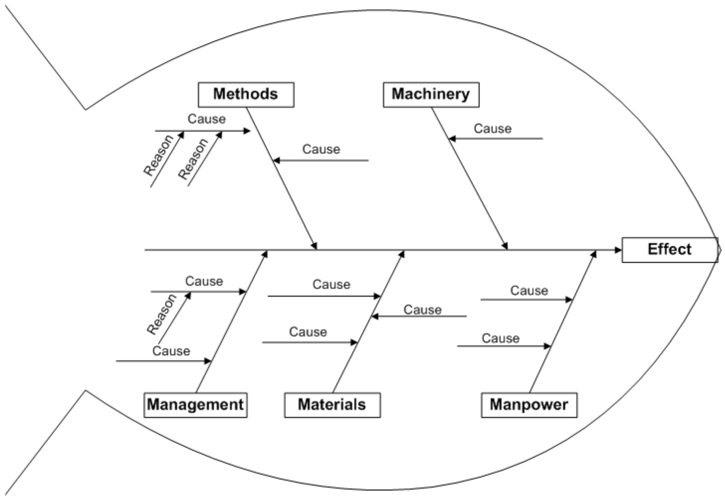

Figure 5. Fishbone Diagram (Envision Software, 1998).

Following, it can be verified the main causes of experimental errors in this work, which are organized by the Method of 5M.

4.1 Details of the Applied Methods

MANUAL IMPREGNATION OF RESIN IN THE FIBERS WITH CONSOLIDATION IN VACUUM: The resin impregnation of the fibers must be homogeneous throughout the repair. Otherwise, the impregnation can modify the efficiency of the repair. Moreover, the thickness of the manufactured repair does not coincide accurately with the theoretical ideal thickness, so this difference can modify the results. A method to manufacture the composite repair by using machine in the next studies should be adopted.

CUT OF THE PIPES: As it was carried through in manual way, it is possible to produce specimens with different lengths, and with lengths different from that one used in the theoretical analysis. This can influence the analysis and make the experimental results more distant from the theoretical ones.

PROCESS OF GEOMETRIC CHARACTERIZATION OF THE PIPES: This identification has many errors associated, therefore the points of measurement in the pipes are not regularly spaced between themselves and have accumulation of instrumental errors (of caliper, ruler, radius meter - the measurement depends on the sensor in the surface of the pipe, and software), which have different resolutions. These errors contribute for the measurement uncertainty. It can be minimized, by increasing practical exercises with these instruments for the operator.

PROCESS OF MEASUREMENT THE RADIUS AND THE THICKNESS OF THE SPECIMENS IN SOME POINTS, TO MEET THE AVERAGE: Certainly, it is even considered that the pipe has a little variation of its radius and thickness. But it is not right, because these parameters vary throughout the pipe (it has imperfections due the differences in the manufacture process). After that, the measurement instruments also have errors associated. More points measured, more real the value of the average of the thickness and the radius.

VERIFICATION OF THE TYPE OF STEEL OF SPECIMENS: In the analysis, the hardness of the steel pipe was verified. It had the common imperfections in the measurement sphere, so the hardness results can present errors. Moreover, this joined value is an approach of the hardness of the material, since it reflects the value of the superficial hardness of the material, and not necessarily of the material as a whole. It can be considered, in the next studies, to add other tests in the identification of the accurate type of material of the specimens.

PREPARATION OF THE COVERS AND THE SPECIMENS: It is possible to occur circumstances in the operation of the specimens, in the lathe for example (as shown in Figure 6), that can modify the results. At the moment of reducing the thickness in the lathe, for example, the region machined in the pipe can be irregular, causing great error of circularity, due to vibration of the pipe and tool used. Thus, the theoretical analysis does not necessarily consider the real pipe used in the experiment (it does not consider irregularity in the roughed-hew region). So it can generate differences between theoretical and experimental results. It can be used, in next studies, more modern CNC machines and new tools in the preparation of the specimens.

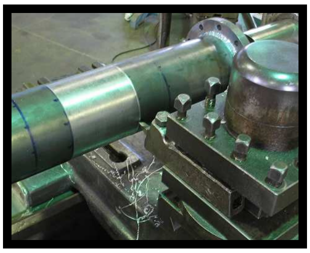

Figure 6. Preparing the specimens.

4.2 Test Conditions

POSITION OF THE SPECIMENS IN THE TEST RIG: The disturbances and vibrations in the two supports can modify the experimental results. Moreover, these supports can not be accurately in the same height, modifying the position of the pipe. Moreover, there is friction between the support and the pipe, mainly during the axial displacement of the specimen. This friction is not considered in the theoretical analysis and can modify the experimental results. Moreover, as the left support is fixing the pipe and the right one is not (as shown in Figure 7), the extremity of the pipe in contact with the left support doesn't have the same deformation than the other side (harming a homogeneous deformation of the pipe). For next analysis, the two supports must be, exactly, of the same type.

Figure 7. Specimens fixed in the test rig with supports.

EQUIPMENT FOR DATA ACQUISITION ADS 2000: As any electric equipment, this device can present trend and, when not correctly calibrated, it can modify the results. A necessary time must be waited, before using it, to make possible the stabilization of the system and its measured values. Moreover, it must be calibrated frequently and in accordance with its manual.

PRESSURE TRANSDUCER: If the transducer or the multimeter (that measure the stress used for excitement) is not correctly calibrated and in good working conditions, they can harm the results. These equipments must frequently be calibrated.

HYDRAULIC PUMP: The pump presents some errors associated that can influence the results. The pump has to be in good condition, has to be used with the correct fluid, has to be kept in a good environment and must not exceed its allowed maximum pressure.

OIL OF THE COMPRESSOR AND INSIDE THE PIPE: It can generate micron-modifications in the internal surface of the pipe. Moreover, after years transporting oil, the pipe can have fatigue. Thus, the type of the used oil can modify the results. The viscosity of the oil used must be checked frequently during the experiment, to prevent the alteration of admitted pressure.

STRAIN-GAGES: The excess of pressure in the specimens can generate a stretching of the terminals welded (see Figure 8) and can generate a contact between the terminal and the steel pipe. This contact provokes a short circuit and avoids the correct performance of the strain gage. Moreover, the composite material has irregular and different behaviors when submitted to pressure and it is difficult to fix the gages in the composite repair.

Therefore, the values obtained from gages in the repair zone are not so trustworthy as the values obtained in the rest of the steel pipe. We have to take care about the position of the terminals and strain gages in the pipe, before starting the experiment. Moreover, it is important to remember that gages cannot be glue next to the sewing of the pipe or the wrinkling of the repair. The methodology to glue the gages in the repair zone has to prevent that the repair surface influences the measurements of the strain gage.

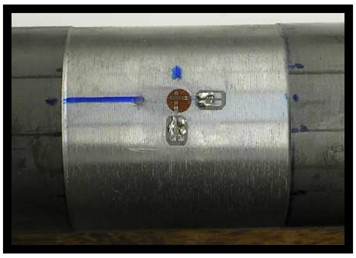

Figure 8. Specimen ready for the experiments.

HOSES OF LINKING BETWEEN THE PUMP AND THE PIPE: The hoses have strengthened rubber walls with steel mesh, beyond copper connections in the entrance of the pipe and the exit of the pump. They can suffer micron-deformations that make it difficult the pressurization of the pipe. It is important to make good connections for preventing accidents.

4.3 Materials and Equipments

AISI 1010 STEEL WELDED PIPE: The longitudinal weld of the pipe is characterized for presenting high mechanical resistance, dimensional variations and located microstructural alterations. The welded sewing increases the local strength and stiffness of the pipe, minimizing the deformations in this region and modifying the natural behavior of the pressurized pipe. The sewing and other factors influence the axial and circumferential results. The sewing harms the analysis of circumferential deformation, since the surface of the pipe next to the weld deforms less than other region, causing a pipe ovalization and an alteration in its global deformation. About the axial deformation, the sewing also influences it, since, throughout the length of the pipe, the region next to the weld deforms less than the diametrically opposing region. Finally, after the failure of the repair, the pipe central region increases its volume and then minimizes the internal pressure (it varies the pressure very fast and can modify the results). It can be suggested that, for the next experiments, the steel pipe has no weld, so it could be more homogeneous and have mechanical properties more predicable.

REPAIR OF COMPOSITE MATERIAL: It has high efficiency, low weight and accessible cost. However, after suffering high pressures, it can delaminate and modify its mechanical behavior (as presented in Figure 9). Moreover, the composite has variations due to hygrothermal effects. The hygrothermal analysis in the repaired pipe with different materials can be developed in future studies.

Figure 9. Repair delamination.

FIBERS WITHOUT PRECISE SPECIFICATION: It was necessary to use elastic, physical and mechanical properties for these materials, because we didn’t have the technique specification for them. In next studies we can try to find out their properties by experimental analysis.

COVERS OF THE PIPES: Exactly after facing of the covers, it can remain barbs, that increase the superficial rugosity and difficult the covered of the pipe. Moreover, the TIG welds of the covers, as illustrated in Fig. 10, can have pores and problems that could hinder an adequate internal pressurization. Before the pressurization of the pipe, an inspection with a penetrating liquid in the weld of the covers can be done.

Figure 10. Preparing the covers.

LITTLE SPACES IN THE REPAIR: Normally, for higher pressures, the values of pressure visualized in the computer by ADS 2000 equipment, are practically constant throughout the time. But some pores can intervene in the results, mainly for low pressures. For higher pressures, the pores are reduced and the values for deformation read by the gage are more steady and with lesser band of variation.

O-RING'S: When the specimen is subject to high pressures in the rupture behavior, we can see that the O'Ring is intense and permanently deformed, so it can't be used in another experiment. In an elastic regimen, the O'Ring does not disaggregate itself and can be used again.

PLACE OF THE REPAIR FAILURE AFTER ITS RUPTURE PRESSURE: It depends on the position of the sewing (failure occurs far from the weld) and the position of the failure of the steel pipe (normally the failure of the repair occurs next to the region of the pipe failure, because it is the place of higher deformation, as shown in Fig. 11).

Figure 11. Place of the rupture in the steel pipe.

MASSIVE CYLINDER OF NYLON: This cylinder of nylon, as illustrated in Fig. 12, can be deformed internally and absorb oil, making it difficult to pressurize the pipe. Moreover, in order to this cylinder does not influence the results, its central axis has to coincide accurately with the axi-symmetrical axis of the pipe. It can be used cylinders from other materials in the next experiments.

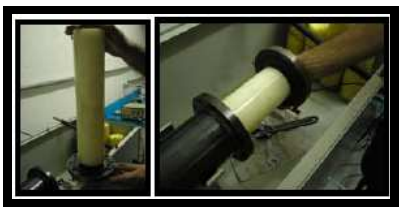

Figure 12. Adding nylon cylinder.

4.4 Environmental Conditions

EXTERNAL VAPORS, GASES, HUMIDITY IN GENERAL, POLLUTION AND OTHER EFFECTS: They can modify the material of the surface of the pipe, provoking points of corrosion.

CONSTANT TEMPERATURE AND HUMIDITY (IDEAL VALUE OF 25°C and 50%, RESPECTIVELY): During the experiment, it can have considerable variations in the temperature and humidity of the environment, because of the electric equipment, excess of operators indoors and door of the laboratory opened, for example, that provoke an increase of the temperature. To control the acclimatization of the laboratory, it was necessary to measure the temperature and humidity constantly.

NOISE IN THE ENVIRONMENT: Currently, the verification of the beginning of the fibers rupture is made with acoustics emission (Hull, 1988). In a specific pressure, some staple fiber sounds start to be heard. Thus, noise in the experimental environment can harm this kind of perception and influence the analysis. To avoid this noisy, we have to inform officially, in the moment of the experiment, that it cannot have sounds next to the laboratory.

SPECIMENS SUFFERING CONTACT WITH WATER AND OTHER AMBIENT AND CHEMICAL VARIATIONS: A small corrosion can be started in the machined specimen, because when we machined the pipe we removed the protective layer of the steel, which is adhered to the external surface of the original pipe. We have to prevent the contact of the specimens with water and to protect its surface with some anticorrosive substance.

4.5 Human Errors

THE ADHESIVE OF THE STRAIN-GAGES AND CONNECTORS AND THE WELDING OF THE STRAIN GAGES TERMINALS ARE MADE MANUALLY: Any human error when he glues the strain gage and connectors in the specimens, mainly related to its position and direction, can modify the measured results of deformation. Moreover, the operator must have much ability to weld the terminals of the strain gages in the pipe, without harming it. No strain gage can be located in the upper/lower part of the transversal section of the pipe, exactly to prevent that the small deflection existing in the center of the pipe influences the results.

THE PROCEDURE OF THE REPAIR MANUFACTURE IS MANUAL: The operator must have experience, ability and caution to promote all the preparation of the composite repair (taking care of the correct fiber mass, the way to roll up the repair in the pipe, as shown in Fig. 13, the way to make a resin impregnation and the time of cure), to prevent problems in the repair. For example, to make the matrix (resin + catalytic), the adequate ratio of the mixture in weight is of 100 (resin epoxy) for 13 (catalytic). The mixture must remain in clean containers and be put into motion during 3 minutes to get a homogeneous result. But, when the operator doesn't have practical experience, this mixture may not be in the ideal accurate ratios, may not be constituted during the adequate time and may include impurities in the process. All these errors can harm the efficiency of the repair. It can be considered to automate the repair manufacture process, adding automated technologies.

Figure 13. Preparing the Composite Repair.

THE SETTING OF THE COVERS WITH SCREWS IS MANUAL: Any screw badly pressed (see Fig. 14) can modify the experiment. The maximum torque admitted must be calculated to avoid problems.

Figure 14. Preparing the Covers.

THE CALIBRATION OF THE DATA ACQUISITION SYSTEM DEPENDS BASICALLY ON THE OPERATOR: When calibrating the system of data acquisition, it automatically chooses the best resistance of calibration for the work limits, depending on the sensitivity (or gain) of each sensor connected to the system. However, the value of this gain is selected and adjusted for the operator and, in some cases, the operator must readjust the value of the gain. It is necessary that the operator knows how to calibrate this equipment, to avoid selecting wrong values and harming the experiments.

THE MEASUREMENT WITH CALIPER, THERMOMETER, RULER AND SPHEROMETER IS BASICALLY VISUAL: There are many errors associated of hysteresis (for radius meter case) and of parallax (visual error because of human position). To prevent these errors, the operator cannot be stressed and must have visual concentration at the moment of the measurement.

5. CONCLUSIONS

Within the context of this work, the actual necessity to repair damaged steel pipes, in practical situations, could be verified. Because of its excellent properties, that were verified in the composite repair used in the experiments, it was possible to see why it is increasing the use of the composite material over the world.

Then, to make an analysis of the complete experimental methodology, the Method of 5M was selected (within the scope of Ishikawa diagram), which is very efficient in the determination of the causes of the errors that can influence the experimental results, and, in addition, helping to prevent them.

This Ishikawa Diagram was also important because it can present some suggestions of improvement in many stages of this experimental methodology described. Moreover, with the description of the experimental analysis, obtained with the Method of 5M, it could be verified that there are some disadvantages in this methodology of composite repair manufacture, which is the crucial and critical stage of the experiment.

Finally, it could be understood how to make an experimental analysis by using the Method of 5M. And much more: it was verified that using a methodology to detect the causes of measurement uncertainty and errors, many procedures and materials can be improved, in order to optimize all the experimental methodologies adopted, improving in consequence some results and conclusions needed in any area of engineering.

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