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EDUCATIONAL EXPERIENCE BASED ON INVERSE ENGINEERING TO EXPLAIN THE EMBRITTLEMENT OF MATERIALS. METHOD BASED ON REAL CASE STUDIES

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Abstract

This study describes an experienced teaching method in the subject of Materials Science, which is studied in the framework of different degrees at the Universitat Politècnica de València, Spain. The main objective of this method was to motivate and stimulate the student's interest through to study relevant and real consequences of materials failures. The method was conducted by analysing real examples of aeronautics failures that occurred in the aerospace and aeronautical industry. The case studies described in this experience were the Challenger shuttle and the comet plane catastrophic failures. In order to verify the validity of the teaching experience, the students' perception compared to the traditional teaching method was taken into account. On the other hand, the positive results were seen through the evaluation proposed in the curriculum. Collaterally, the ethical sense and good practice is commented and worked on, a subject that is very important and sometimes little worked on in our classrooms. It can be concluded that the use of reverse engineering is of high interest to students and allows some basic concepts of materials science to be explained in a more global way than when they are traditionally explained in the master class.

Keywords: Educational experience, Inverse engineering, Material science.

1 INTRODUCTION

This experience was developed in a session that corresponds to the mechanical properties of materials. Previously to this experience, students have had empirical experience of how to determine the elongation of a material for a given force. This behaviour is visualised and experienced in a previous practical session, by acquiring the deformation response of the material as a function of the stress applied by a universal testing machine (stress-strain diagram). In the same session, they understand that the material deforms under elastic way up to a stress threshold. Overload this yield stress the material starts to deform plastically until its failure occurs. At the end of the previous session the students have analysed the obtained responses and have managed to understand the types of deformation of a material. At this point, it is explained that the resistance of materials (maximum strength supported by materials) obtained by means of stress-strain curves. This experiment gives the strength obtained under ideal and optimal conditions; this is, at room temperature and with materials without evident defects. With these previous experiences the session object of this study begins. Using the method described in this study, students will discover that some aircraft and spacecraft exploded because engineers did not take into account (a) the low temperature influence and (b) mechanical stress concentrator defects. However, the resilience of a material that describes the energy that a material absorbs before breaking, it can be obtained by an impact test. This test is performed using a pendulum (Charpy or Izod). This method allows making the experiment under different temperatures from those in the laboratory. In addition, the effect of notching on the maximum resistance of the material can be analysed.

The teaching method described in this article was followed to explain how temperature and notch radius affect the resilience of a material and was then analyzed with the experimental Charpy Pendulum method available in the laboratory. By studying the accident of the space shuttle Challenger due to low temperatures and the airplane Comet due to the fatigue of the materials and stress concentrator, the student was motivated to focus his attention on the importance of this knowledge. Thus, our intention was to increase the interest through the study of accidents that have occurred and their consequences, caused by wrong decision making, in terms of the behaviour of the materials in service.

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2 METHODOLOGY

The following text is a chronological description of how the theoretical-practical class is carried out in order to be able to use this document as reference material for those teachers who wish to repeat or use this teaching method. By initially using a PowerPoint presentation, a first image is shown. This frame serves as a reminder of the conclusion reached in the previous class. We believe that devoting a few seconds to remember the conclusions of the previous class, as well as closing each session with a series of partial and global conclusions, serves to highlight the important concepts. The image presented in class corresponds to that showed in Figure 1. This image serves to remind to student "-...*that a material supports a maximum effort (strength), beyond which, it fails and breaks*. The breakage can be fragile or ductile and the stress-strain response indicates the degree of ductility and stress achieved". The teacher remarks, "-... *Now!, this happens when conditions are under controlled laboratory conditions, that is, at room temperature and testing a material without any type of defect. In today's class we will understand what happens when the material is subjected to low temperatures and/or when it has defects of the crack or a notch* ". This sets the goal for the class in question.

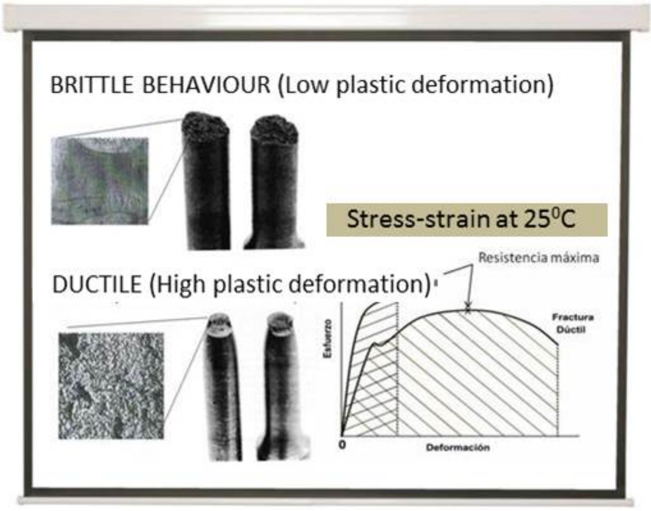

Figure 1. Slide summarizing key points from the previous class.

Below is an image of the different aircraft of NASA's space shuttle program, Figure 2. It is important to have good quality images, in our case they were obtained from the internet free of copyright. At this point we managed to get the student's attention. We explain why was designed the Challenger shuttle and with another slide, it showing an overview of the ship including the tank and engines, while briefly explaining the parts of the rocket and shuttle. Then we watch a video of the launch where the moment of the explosion is recorded. At this point we comment in detail how the commission of inquiry is organized and recommend the book of R. Feynman[1], American physicist and Nobel Prize winner, who researched and documented the accident, in case anyone is interested in further research on this topic.

Figure 2.- Slide shown in class with the different shuttles used in the NASA space program.

Another slide, Figure 3, shows two important facts; first; that the temperature of the launch area was -13ºC (ice suckers are seen, Fig.3a), and second; the moment of the takeoff a gas leakage is appreciated in the joint of one of the engines (Fig. 3b). These facts are noted and it is explained that the area where the leakage is registered coincides with two parts of the engine where some O-rings should seal both parts. Richard Feyman, in addition to other investigations that he was able to make at the Kennedy Center of NASA, verified and later demonstrated in a public press conference that by submerging these rubbers in a cold liquid their behavior changed, becoming more rigid.

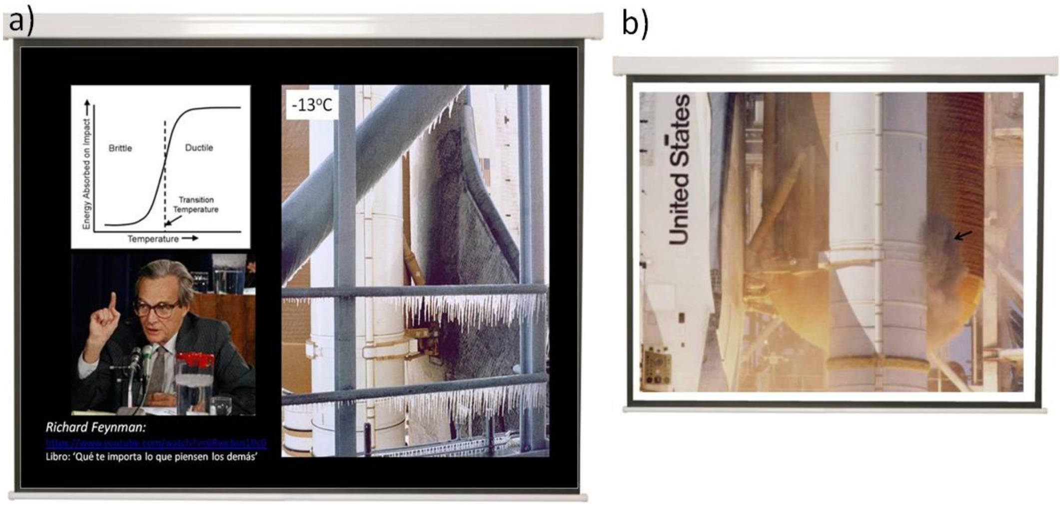

Figure 3.- Slides used to demonstrate that a), that the temperature at the time of the launch was very low, b) the gas leakage captured in the later sequence of the launch. The first slide also includes a photograph of R. Feynman with a jug of cold water that he used during the Challenger Research Commission hearing.

At the end of that investigation, they concluded that the O-rings had lost resilience (this is explained in depth in class) due to the effect of cold temperature and therefore were not able to absorb the necessary elastic energy produced by the engine vibrations and thrust. Thus they did not properly accommodate to the deformation. This fail provoked a leakage of gases at high pressures and temperatures. This situation continued during the followed seconds after the launch until the material could not withstand any more pressure and a crack started. Finally, the entire engine wed destroyed generating the subsequent disintegration of the ship.

To conclude this story, we list the reasons that pushed the mission leaders to launch even against adverse conditions, since we think that the student and future engineer must also be educated in values and good practice to see the scope of decisions made under pressure. Briefly, we have the help of an image, Figure 4, which was the first time a civilian female astronaut traveled into space. Her name was Sharon Christa Corrigan and she was a school teacher. That day the president of the USA, Ronald Reagan, was giving the nation's speech and it was considered important to boast of the fact that a school teacher would be giving a live class to all public schools, in addition to a video conference scheduled with the president for that time. Finally, it is concluded that temperature affects the behavior of materials, and if a different critical temperature is exceeded for each material, it can lose ductility to reach a behavior of fragility.

Figure 4.- Slide used to show the moment of the Challenger's explosion during its launch. The crew is also shown with the civilian school teacher in addition to the moment when Ronald Reagan shows his condolences in the nation's speech. These images serves to explain the importance of maintaining good professional practice when working under pressure and under the influence of the media.

Finally, other examples are described, supported by slides, where some type of failure in service of the materials occurred due to the unexpected brittleness effect of low temperatures. At this point it is already clear to the student that by cooling a material, its resilience (energy absorbed elastically) can be reduced. It now remains to describe the effect of notch type defects on impact resilience and the experimental methodology required determining their degree of influence experimentally.

To introduce the student to the effect produced by a notch in the surface of a material, the photoelasticity experiment is theoretically described by which it is possible to observe the distribution of stresses inside a material. By means of Figure 5 is explained the configuration of this experiment.

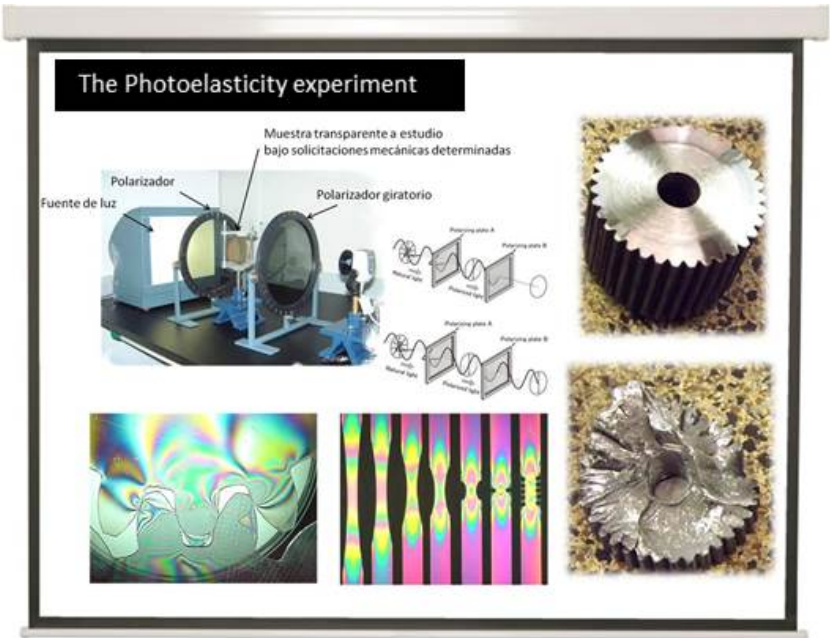

Figure 5. Slide showing the photoelasticity experiment, an example of the notch brittleness effect and examples of results of the experiment showing the heterogeneity stress distribution inside a material.

Using web material from open-courses, in this case from the University of Cambridge, DoiPoMS[2], we visualize and explain what happens to the mechanical stresses in a material when it has a notch on its surface and the it is subjected to a tensile stress. Figure 6 shows an outline of the video sequences projected in the class. It is explained as the student observes that a notch in the surface of material causes the stresses within the material to be concentrated at its apex. In this way, the concentration of these shear stresses in a single point or area of the sample favours the rapid growth of the crack, thus decreasing the energy (mechanical stress) that the piece can withstand before failure under stress. Examples are given of pieces where this stress concentrating brittleness effect is usually evident, such as bolts, gears and angular shapes.

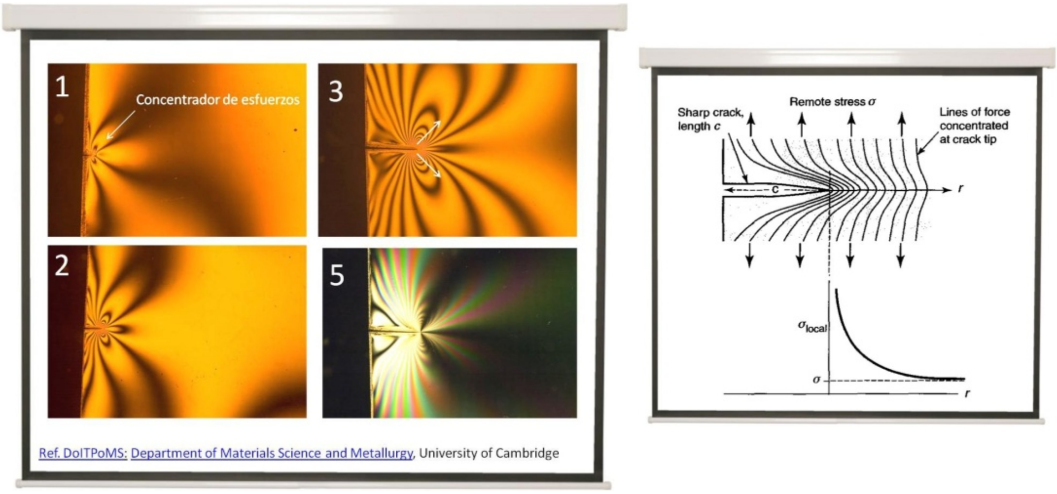

Figure 6. Sequence of a surface crack (notch) growth where it is observed how stresses are concentrated in the vertex. The stress lines are revealed by photoelasticity test.

It is also explained that there are programs and specialized software to model this possible stress concentrator or notch effect in order to predict, forecast and at the same time minimize these failures. Finally, some examples of failure are commented where both types of fragilisation mechanisms converged, low temperature and notch defectology. In this case, is cited the sinking of the SS Schenectady in 1943. Once all of the above has been explained in the theoretical session, we move on to the practical session. In this session the necessary instrument is available to carry out a resilience test to the presence of notches in a material. In this case we use a 300 J Charpy pendulum. This large pendulum has a mass of 19 kg suspended at 1.4 m from the ground. The size of the equipment often impresses and attracts the attention of the students. It is not the purpose of this paper to describe the equipment, types of specimens or experimental procedure. It is no longer considered an innovative part of the teaching procedure and this information can be found, for example, in the testing standard or in any type of specialized literature.

We will say that the students try out several test pieces at impact and at room temperature (~24ºC) where the notch radius varies from a sharper vertex to a higher vertex radius (softer notch). In this way they record the resilience obtained in the test as a function of how sharp the notch is (the stress concentration decreases as the radius increases and therefore greater resilience should be observed). In addition, samples with the same radius previously cooled in a freezer to -20ºC and others to 400ºC are tested in order to compare the resilience obtained for the same notch radius at three temperatures.

By discussing the obtained results, they are asked to analyze and predict what would happen to a real and complex mechanism, in this case a passenger plane, the Hallivan DH.106 Comet of 1949 like the one shown in figure 9, where large windows with sharp corners and riveted to the fuselage were installed, knowing that an aircraft is subjected to large and complex cyclical stresses at temperatures as low as -60ºC during its service.

Figure 7. First version of the Comet plane that used riveted windows with square shapes of sharp vertices.

3 RESULTS

The best way, from our point of view, to check if a teaching method is valid for a specific class is, on the one hand, the perception that the students maintain an active and participative attitude during the class and of course, that at the time of the evaluation it is known that the subject matter has been well understood by a large part of the students evaluated. In this case, it was found that when asked to predict the possible problem of the Comet plane with sharp corners and rivets in the windows, practically the majority of students (~97% of students evaluated) answered correctly, this is, that stress concentrators would reduce the strength or resistance of materials and could cause failure and breakage of the material. To the next question of how to solve the problem if it existed, all students agreed on giving the right solution; *rounding the shape of the windows and release the rivets*. The images in Figure 8 graphically corroborate the solution provided.

Figure 8. Slides shown after asking students about their impression of what might happen and what their solution would be.

Finally, the student is asked to make a graph with the values obtained during the practical session with their subsequent necessary mathematical calculation. We think and take in value that engineering student gets used to present as much as possible the empirical results by means of graphs. In work meetings, seminars, reports, congresses, etc., he will have to use and know how to interpret graphs correctly. The following Figure 9 is a graph made by a student, showing correctly the axes, units and facilitating the understanding of the results. In this case it is very simple to check the trend of a mechanical behavior with respect to the test variable, in this case the temperature.

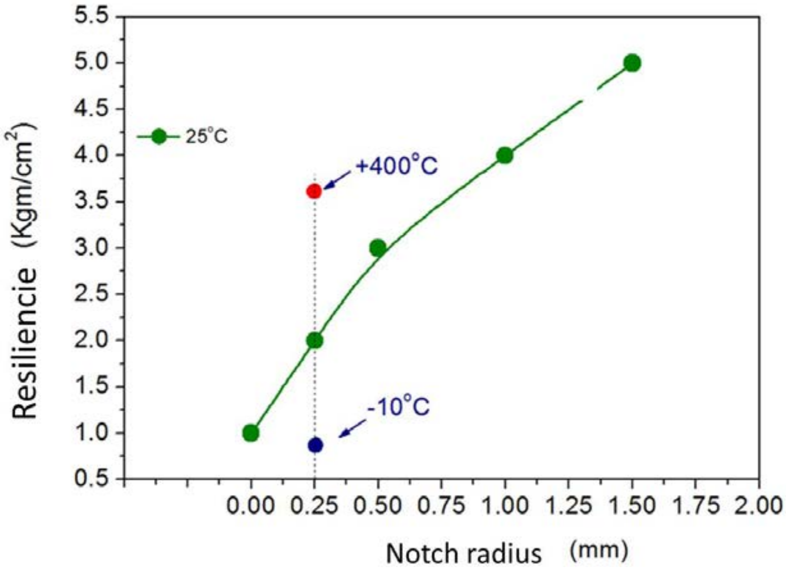

Figure 9.- Example graph made by the student representing the resilience obtained against test temperature and notch radius.

Finally, the student is asked to interpret the results that they obtained, asking him or her to justify the behavior observed according to the content developed in class.

4 CONCLUSIONS

With this educational experience, there has been an increase in active participation by students during and at the end of the class. In addition to the good understanding of the subject as verified by the subsequent evaluation, it can be concluded that

- A novel teaching method is proposed that includes a study of reverse engineering through the analysis of disasters in aircraft and space shuttles to explain the concept of material resilience. Students see how mechanical properties are impaired by low temperatures and notch-type defects, while understanding the disastrous consequences of this phenomenon, when it is not sufficiently anticipated.
- The students have been well received by the school, showing an active participation and interest in the subject. Moreover, the subsequent evaluation corroborates the validity of the method.
- With this method, it is possible to work on the sense of modelling and forecasting against a certain set of real conditions.
- Finally, it is important to note that, as a side effect, we work on ethics and good practice, which is a very important subject and sometimes not very well worked on in our classrooms, as it is not included in any of the subjects.

ACKNOWLEDGEMENTS

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[1] Feynman, Richard P., What Do You Care What Other People Think?, 1988, W. W. Norton, ISBN 0-393-02659-0, 2001 paperback: ISBN 0-393-32092-8

[2] https://www.doitpoms.ac.uk/