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Detection of Rib Fracture Occurrence During Crash Test

P. Potier and J. P. Lassau

ABSTRACT

It seemed that more information about the behaviour of the ribs during a crash test could be useful, particularly the knowledge of the moment of the rib fracture leading to a better understanding of the behaviour of the thorax according to the loading .
The technique applied consists of the acquisition of data provided by extensometers glued on the medium arc of the rib.
The curves plotted can show some typical profiles related to the events occurring during the test, particularly the time of the rib fracture.
The analysis allows the chronology of the loading of the ribs and the occurrence of the fractures to be determined. Consequently, an evaluation of the evolution of the loading of the thorax related to the time is possible.
The article describes:

- *The technique and the methodology used to instrument the ribs*
- *The complementary device specially designed in order to acquire data*
- *The analysis of the curves according to the results of the autopsy*
- *A proposal of theoretical curves related to the events occurring during the test*
- *The limits of the technique*
- *The conclusion*

INTRODUCTION

The aim of this work consists of the development of a method allowing the moment of the rib fractures to be detected during a crash test. Applying this method leads to the knowledge of the chronology of the rib fractures, a characterization of the effect of the loading pattern on the thorax and a better understanding of the injury mechanism of the thorax.

METHODS

Principle of the technique

The principle consists of the instrumentation of the ribs using extensometers (Figure 1). The extensometers are glued on the medium arc of the ribs. The axis of the extensometer corresponds to the longitudinal axis of the rib.

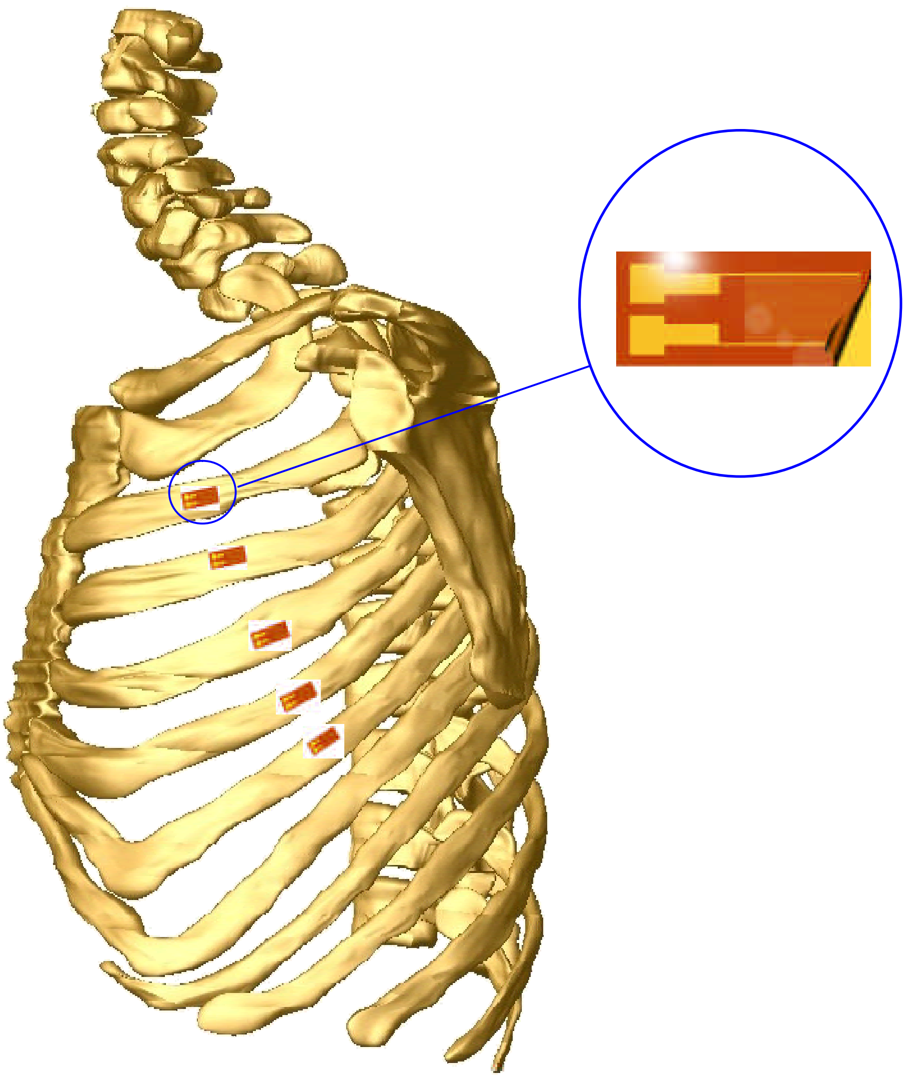


Figure 1: Extensometers glued on the ribs 2, 3, 4, 5, and 6.

Technical solution applied

Preparation of the strain gages (Figure 2)

The strain gages used are 350 ohms constant strain gages. They are fed using 3 armored wires to prevent offset related to the length of the wires and to the electro-magnetic noise. A connector equipped with 3 pins is used to connect the feeding wires to the box including the bridge completion resistors. The connector is secured when plugged in because of the need to board the whole device.

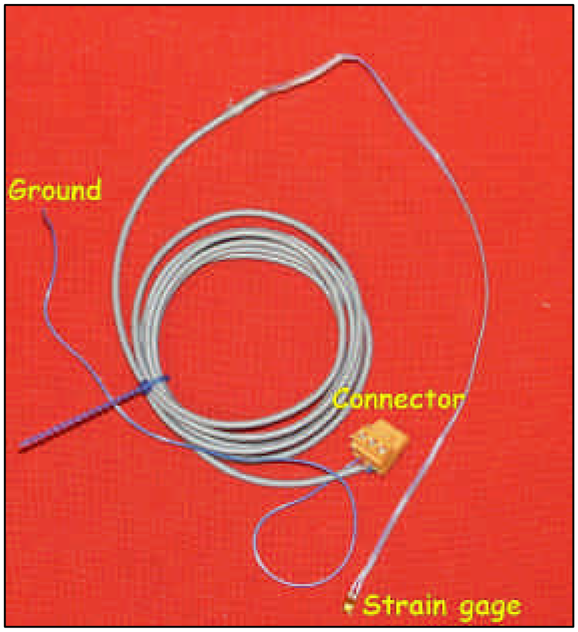


Figure 2: Wiring of the strain gages

When soldering, the plan including the gage and the wires must be respected (Figure 3). Doing this, the wires can be positioned against the rib during the gluing, preventing rupture of the gage.

Figure 3: The wires in grey and the side view of the gage in white

Instrumentation

The strain gages are glued on the rib using cyano-acrylate glue with a catalyst (not an inductor). The use of a catalyst allows the polymerization to occur only a few seconds after the positioning of the gage. The following actions are carried out:

- The glue is spread on the gage.
- The catalyst is sprayed on the rib.
- The gage is positioned on the rib and squeezed using the thumb or the index.
- Fifteen seconds later, the pressure is stopped.
- The wires are fixed on the rib using a piece of non-woven textile impregnated with glue (Figure 4).

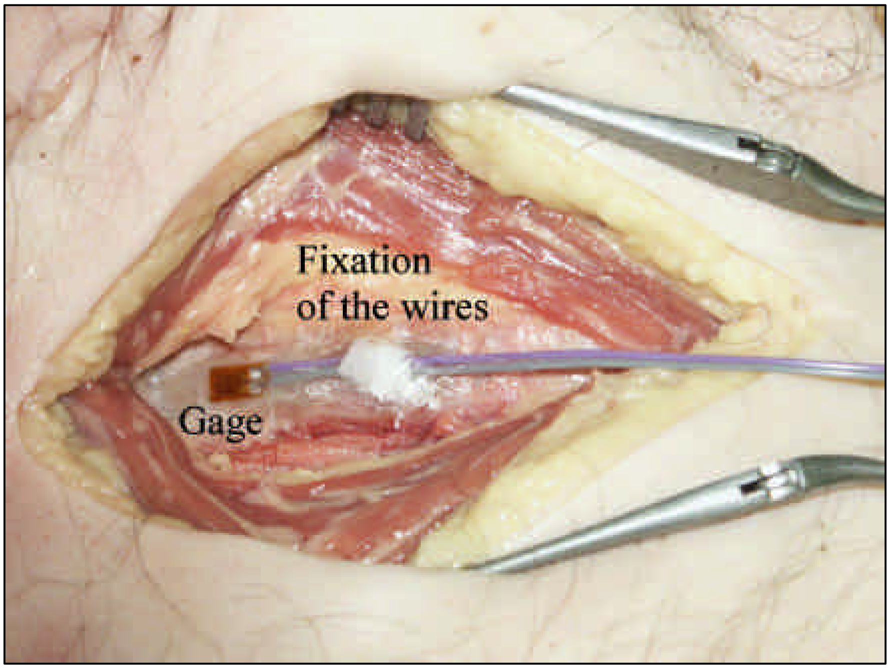


Figure 4: Gage glued on the rib

- A nylon collar is placed around the wires at a distance of 20 centimeters from the gage.
- Loops are made with the wires under the skin (Figure 5).
- The skin is sutured, including the collar between two sutures, in order to prevent wrenching (Figures 5 and 6).

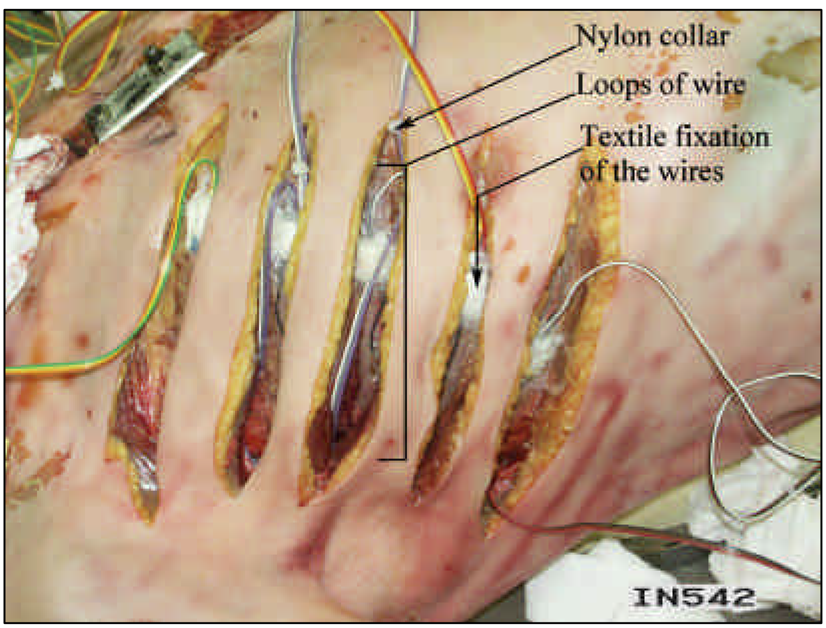


Figure 5: Instrumentation carried out

Figure 6: Side view of the thorax, skin sutured

Verification of the instrumentation

To carry out experimentation with cadavers, it is necessary to manage the biological environment carefully. Consequently, many devices must be protected from contact with the biologically contaminated environment. Because of this, in the field of the instrumentation of the ribs with gages, the wires and the connector are inserted into a plastic bag before the beginning of the work (Figure 7) leading to the impossibility of an easy resistance measurement however necessary to the checking of the gage at the end of the instrumentation.


Figure 7: Connector and lead wires included into a plastic bag

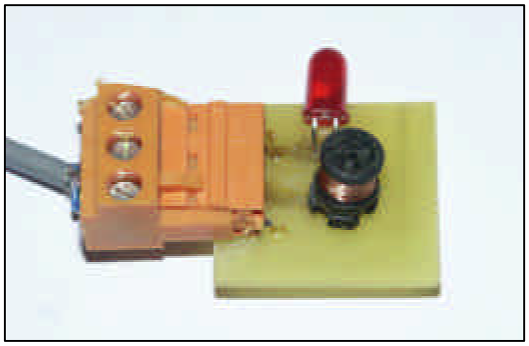


Figure 8: Continuity test circuit

Figure 9: Emitting probe

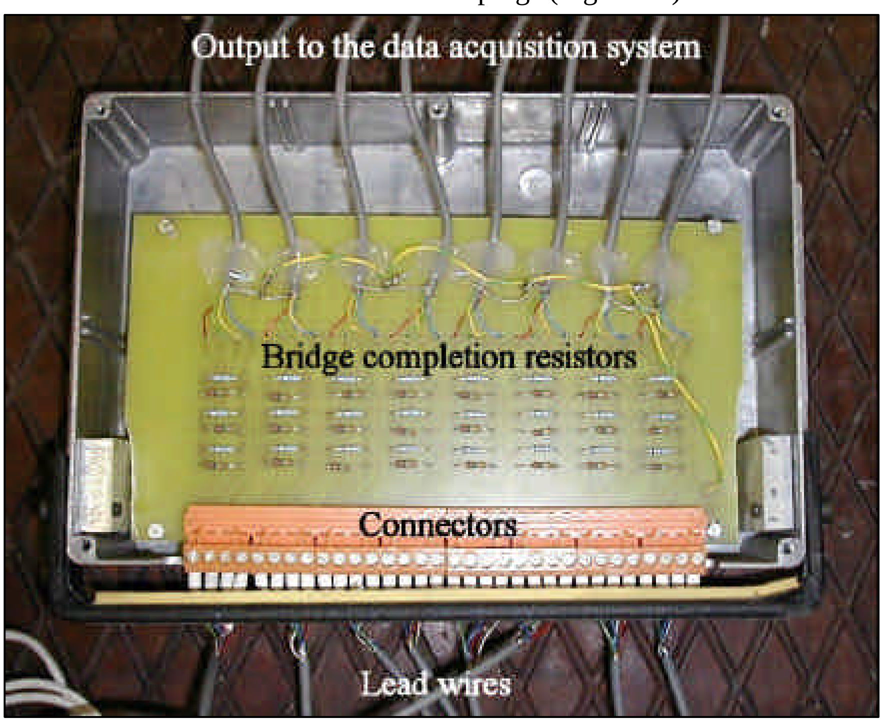
A specially designed device has been developed in order to solve the resistance measuring problem. This device consists of a small circuit (Figure 8) plugged into the connector before the inclusion into the plastic bag and an emitting probe (Figure 9) aiming to excite the small circuit through the wall of the plastic bag. If the continuity of the gage and leadwires is correct, a LED lights into the plastic bag. This technique allows a checking of the continuity of the circuit when critical actions have been carried out. These actions are:

- The gluing of the gage on the rib
- The suture of the skin
- The clothing of the cadaver
- The transportation of the cadaver to the crash test area

If a default is detected, the gage can be replaced.

Complementary device allowing data acquisition

The use of strain gages leads to the installation of an intermediate device including the bridge completion resistors. It consists of a box equipped with input connectors and output cables soldered on the electronic card in order to reduce the number of plugs (Figure 10).



The resistors used for inactive arms are 1% resistors secondarily sorted in order to mount resistors of which resistance is close to 354 ohms (resistance of the gage plus resistance of the leadwires) (Table 1).

Table 1. Example Of Electric Offset Measured For A Measurement Range Equal To 100 Millivolts

N° gage	Offset millivolt	Resistance	Rib
1	6,8	353,8	C6 Droit
2	6,7	353,8	C6 Gauche
3	7,3	353,6	C7 Gauche
4	6,9	352,7	C9 Droit
5	5,4	353,3	C7 Droit
6	7,2	352,7	C8 Droit

The autopsy

The results of an autopsy are necessary so that the data provided by the gages can be analyzed. To obtain a pertinent description, the section of the intercostal muscles must be carried out allowing the rib to be mobilized in order to detect fractures. Secondarily, the bone surface must be carefully scratched so that the characteristic of the fracture can be described.

The data collected are:

- Position of the fracture in relation to the position of the gage.
- Characteristic of the fracture:
  - Cartilage bent or fragmented
  - External, internal or total cortical bone rupture

- Control of the gage:
  - Gage unglued or cut
  - Wire cut

Classification of the fractures on a drawing:

-  Means cartilage bent

-  Means partial fracture of the cortical bone (external **or** internal)

-  Means cartilage fragmented or complete fracture of the rib (external **and** internal cortical bone)

RESULTS

Autopsy result

The result exposed concern a laboratory frontal sled test with a restraint system consisting of a 4 kN load-limiting belt, a pyrotechnic pretensioner and an air-bag. All the rib fractures are shown in Figure 11. On the left side, there were 3 total cortical bone fractures and 1 cartilage bent. On the right side, there were 8 total cortical bone fractures, 1 partial cortical bone fracture, and 4 cartilages bent.

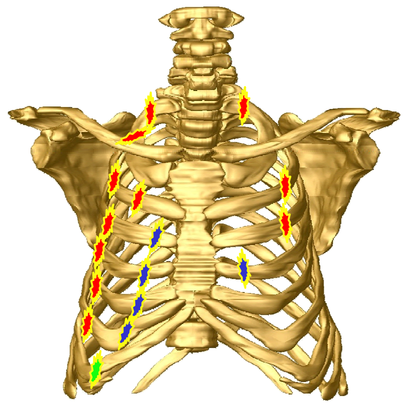


Figure 11

For the instrumented ribs, the situation is the following:
On the left side:

- Rib 2, 1 total cortical bone fracture
- Rib 3, 1 total cortical bone fracture
- Rib 4, 1 cartilage bent
- Rib 5 and rib 6, no fracture

On the right side:

- Rib 2, 2 total cortical bone fractures
- Rib 3, 1 total cortical bone fracture, 1 cartilage bent
- Rib 4, 1 total cortical bone fracture, 1 cartilage bent
- Rib 5, 1 total cortical bone fracture, 1 cartilage bent
- Rib 6, 1 total cortical bone fracture, 1 cartilage bent

Analysis of the curves

Introduction:

Basically, a typical curve of a rib fracture consists of 4 segments:

- The first segment corresponds to the initial electrical level showing the offset of the bridge.
- The second segment corresponds to the loading phase of which the electrical level can range over 100mv. The peak of the curve corresponds to the rib fracture leading to the end of the loading phase.
- The third segment corresponds to the unloading phase because of the deflection occurring on a part of the rib disjointed from the other part of the rib coupled with the spine.
- The fourth segment corresponds to the return to either the initial electrical level in case of elastic behavior or an electrical level superior to the initial level in case of plastic behavior.

Detailed analysis

The test analyzed corresponds to the clarification phase of the technique. This is why the value of the deformation is given using millivolts. Secondarily, the value of the deformation is given using microdeformations.

Table 2. Analysis Of The Curves Obtained During The Test

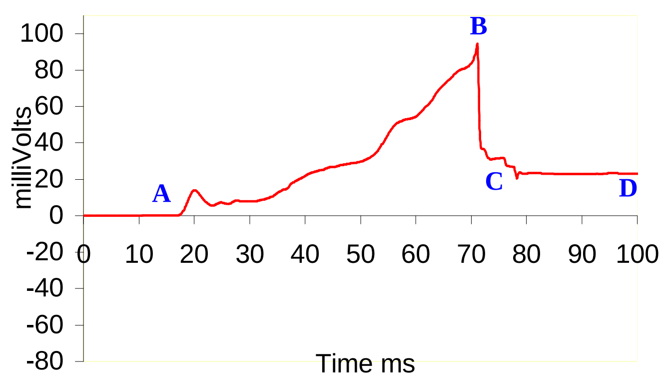
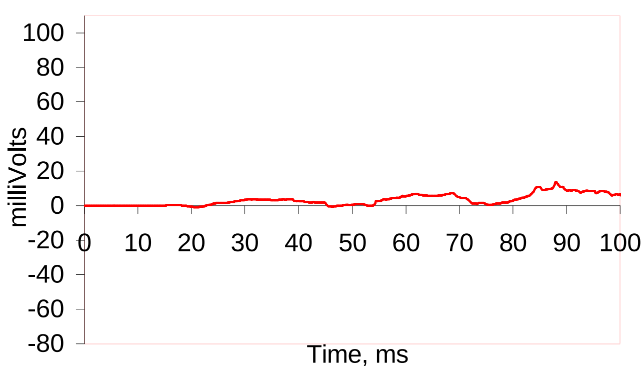
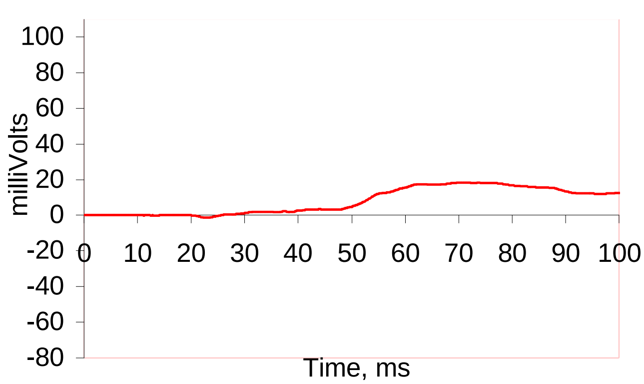
<table>
<tr><td>
</td><td>Rib 2 on the left side:
Segment A to B: loading phase.
Point B : rib fracture occurrence.
Segment B to C : unloading phase.
Segment C to D: final deformation of the rib shown by the electric level higher than the initial level.
Time of the fracture: 71 milliseconds.</td></tr>
<tr><td></td><td>Rib 3 on the left side:
The gage did not work.</td></tr>
<tr><td>
</td><td>Rib 4 on the left side:
The cartilage bent did not produce any interesting aspect on the curve. The profile of the curve shows the loading of the rib.</td></tr>
<tr><td>
</td><td>Rib 5 on the left side:
Lack of fracture. The profile of the curve shows the loading of the rib.</td></tr>
</table>

Table 2. Analysis Of The Curves Obtained During The Test (Continued)

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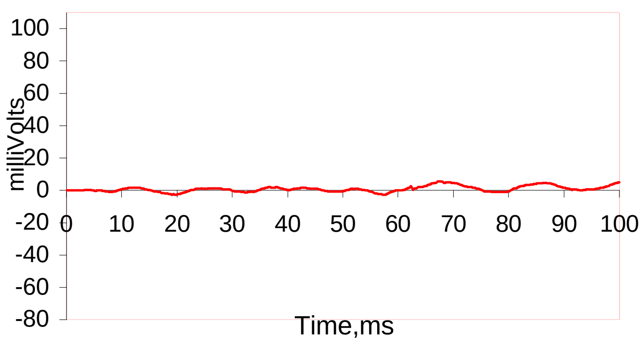
<tr>
<td>
</td>
<td>Rib 6 on the left side:
Lack of fracture. The profile of the curve shows a loading level that is very low.</td>
</tr>
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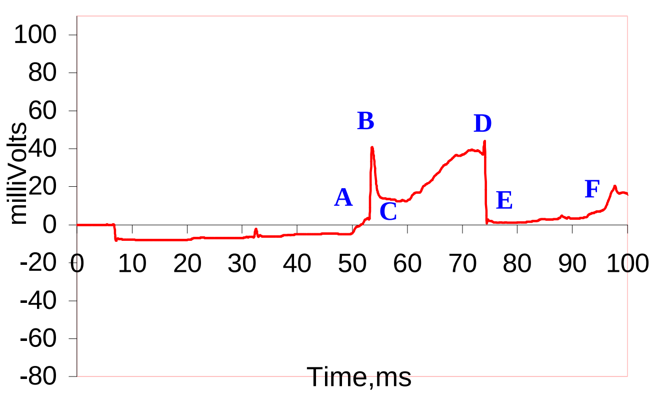
<td>
</td>
<td>Rib 2 on the right side:
Segment A to B: loading phase.
Point B: rib fracture occurrence.
Segment B to C: unloading phase.
Segment C to D: second loading phase of the rib. This is possible if the position of the first rib fracture is anterior in comparison with the position of strain gage. Thus, a second loading phase involves the gage in the deformation of the rib.
Point D: second rib fracture occurrence.
Segment D to E: second unloading phase.
Segment E to F: third loading phase. This is possible if the position of the second rib fracture is anterior regarding the position of the strain gage. If the second fracture is posterior regarding the position the strain gage the reloading phase is improbable.
Time of the first rib fracture: 53 milliseconds.
Time of the second rib fracture: 74 milliseconds.</td>
</tr>
<tr>
<td></td>
<td>Rib 3 on the right side:
The gage did not work.</td>
</tr>
</table>

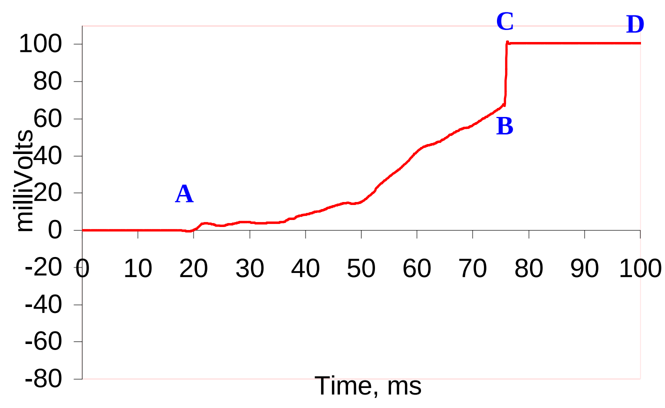
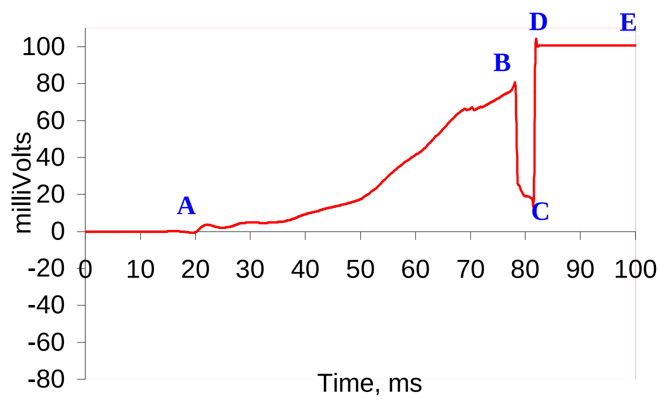
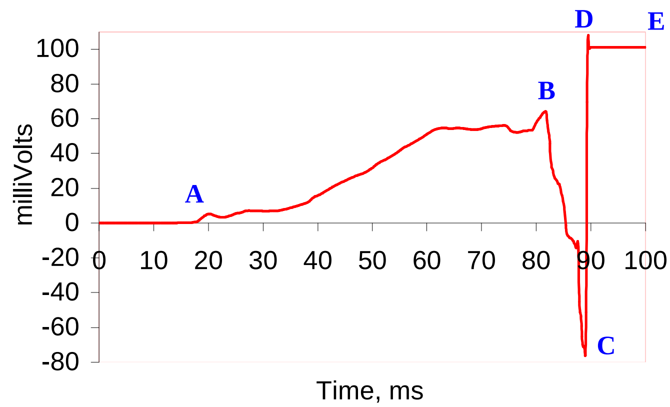
<table>
<tr>
<td>
</td>
<td>Rib4 on the right side:
Segment A to B: loading phase.
Segment B to C: rupture of the strain gage.
Segment D to E: saturation of the electric signal.
The autopsy result aids in the analysis of this curve by showing a rib fracture crossing the strain gage. Consequently, the assumption that the rib fracture and the gage rupture occur at the same time can be made.
Time of the rib fracture: 76 milliseconds.</td>
</tr>
<tr>
<td>
</td>
<td>Rib 5 on the right side:
Segment A to B: loading phase.
Point B: rib fracture occurrence.
Segment B to C : unloading phase.
Segment C to D: rupture of the strain gage.
Segment D to E: Saturation of the electric signal.
Time of the rib fracture: 78 milliseconds.</td>
</tr>
<tr>
<td>
</td>
<td>Rib 6 on the right side:
Segment A to B: loading phase
Point B: rib fracture occurrence.
Segment B to C : unloading phase without explanation for the negative segment of the curve.
Segment C to D: rupture of the strain gage.
Segment D to E: Saturation of the signal.
Time of the rib fracture: 86 milliseconds.</td>
</tr>
</table>

Table 2. Analysis Of The Curves Obtained During The Test (Continued)

Chronology of the rib fractures

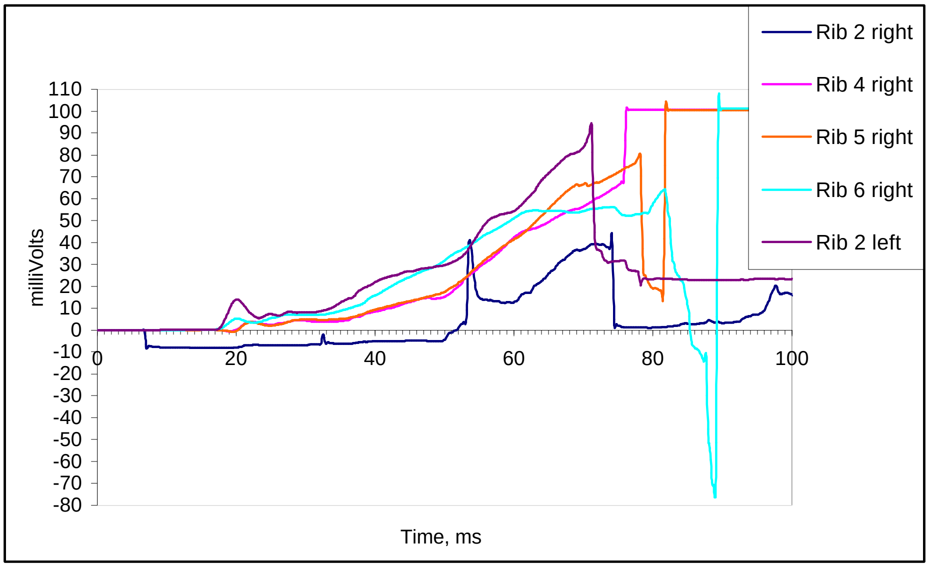


Figure 12: Curves of the ribs with fracture

Table 3. Times And Chronology Of The Rib Fractures

Rib	Time of fracture occurrence	Chronology
Rib 2 on the left side	72 milliseconds	2
Rib 2 on the right side, anterior fracture	53 milliseconds	1
Rib 2 on the right side, posterior fracture	75 milliseconds	3
Rib 4 on the right side	77 milliseconds	4
Rib 5 on the right side	78 milliseconds	5
Rib 6 on the right side	83 milliseconds	6

The chronology of the rib fracture occurrence was determined, explaining the mechanism of chest loading (Table 3 and Figure 13).

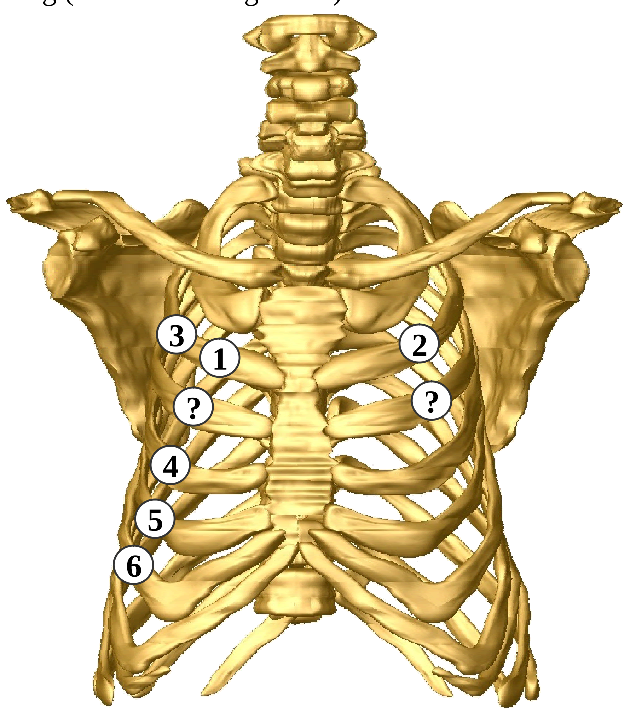
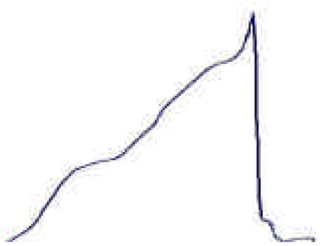
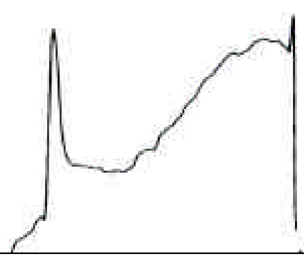
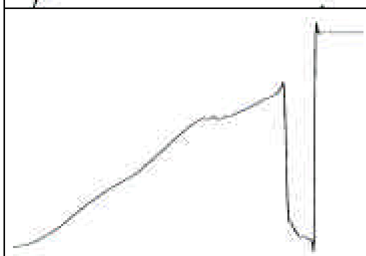
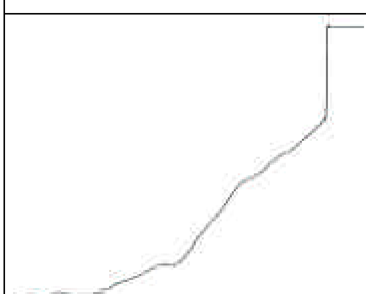


Figure 13: Chronology of the rib fractures

Proposal for a basic guideline allowing for the test events occurring on the ribs to be analyzed

The experience acquired while testing allows for the definition of a guideline that should be applied for the analysis of future tests. Table 4 constitutes the first step of a guideline that could be improved by sharing experience.

Table 4. Typical Profiles Of Curves Identified

	Loading of the rib. No rib fracture.
	Typical curve showing one rib fracture occurrence. The autopsy allows the gluing of the gage to be checked. If the gage is unglued, the analysis of the curve is impossible. Indeed, in case of a rib fracture occurrence, there is no guarantee that the time of the fracture and the time of the ungluing of the gage are the same.
	Typical curve showing two rib fracture occurrences. As long as a rib fracture occurs forward the gage, data concerning the loading are available just at the time of a second possible fracture. Consequently, when instrumenting, it is necessary to try to position the gage as posterior as possible. This principle is true for frontal crashes only.
	Typical curve showing one rib fracture with a gage rupture or ungluing occurring secondarily.
	Typical curve showing a gage rupture or ungluing during the loading phase. The autopsy result is necessary to go forward in the analysis of the curve. The gage can be unglued leading to an impossibility of analysis. The gage can be cut: Either the gage rupture is located on the rib fracture allowing for the hypothesis that the two events occurred at the same time or the gage rupture is located at another place leading to an impossibility of analysis.

CONCLUSIONS

This technique is very useful because of its capability to determine the instant of a fracture and more commonly to know the history of the loading. However, although a very precise methodology is applied, some limits can appear. This means that, in spite of the common profile of curves showing loading only, the autopsy can discover a rib fracture. A first hypothesis can involve the type of fracture to explain the non-typical profile of a curve obtained (cartilage bent or partial cortical bone fracture producing non-typical curves). A second hypothesis can involve the level of mineralization to explain the lack of an unloading phase on some curves although fractures are discovered when carrying out the autopsy.

In conclusion, there is no guarantee of result. But as generally pertinent data are available,

- First, associated with the results of the autopsy, it allows the occurrence of the rib fracture and the pattern of the loading to be linked (shape of the loading affects related to the type of restraint system).
- Secondly, it can be assumed that, as experience is gained with this technique, it could help in better understanding of the injury mechanism of the thorax.

ACKNOWLEDGEMENTS

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DISCUSSION

PAPER: **Detection of Rib Fracture Occurrence During Crash Test**

PRESENTER: ***Pascal Potier, Centre Europeen de Securité et d'Analyse des Risques***

QUESTION: *Richard Kent, University of Virginia*

First, let me congratulate you on working your way through that. We've done that kind of thing a couple of times, and that's terribly labor-intensive to put all those on and to get them to work, and you actually got a higher proportion of them to work than we do. They either get disbonded or their leaves will come off. You're doing a very nice job with a difficult experimental problem. One thing we've done to address the first conclusion to guarantee a result and at least give yourself a little bit better feeling about it is to put an acoustic sensor or more on the ribcage. And, we've been able to pick up fractures quite remote from the gage. And so, that may be a way to somewhat validate, or at least confirm to some extent, the results you're getting. Another advantage of that is you may pick up a fracture on a rib where you don't have a strained gage. So if you get fractures that are not on ribs you've instrumented, the acoustic sensor may pick them up. So, it might be something to think about because it's very easy to put, much easier than this. I guess it was mostly a comment.

Q: *Guy Nusholtz, Daimler/Chrysler*

First, sort of a technical question: Did you have any problems with the ribcage with the gages floating off the ribs because of water coming up from underneath?

A: Sorry?

Q: There's fluid in the ribs. The ribs have fluid in it, so you have to clean the ribs before [Yeah.] you put the gage on. After you clean them, were you able--Was there a time factor?

A: To glue? You're saying it's really difficult to glue the gage.

Q: It's difficult to glue the gage. But then over time, water will come up from underneath and float the cage. You know, if you wait, like, 10 hours.

A: It was a problem at the beginning, but I have not detailed the technique to glue the gage on the ribs. But once the bone is scraped, we use--I say it in French: *acetone*. Do you understand?

Q: Yeah, yeah. Okay.

A: To remove fat, you see? And, we do this a few times and then it's possible to glue, but it's important to use what I said: not an inductor but a catalyst. Consequently, the gluing is very, very short, just few seconds. A few years ago, it was very difficult and sometime we needed half a day to glue two gages. And now, it takes 10 minutes and it works each time.

Q: Very good. In some of your traces, it looked like you had hardening going on in the ribs. Did I read the traces correctly?

A: The curves?

Q: The curves. It looks like before you have fracture, you have a hardening going on. In other words, the rate increases for a short period of time before it fractures.

A: I'm sorry. I don't understand very well.

Q: Can you go back with some of your curves and I'll point it out?

A: Yeah.

Q: And most -- It looked like in most of the strain gages, it looks like you've got a hardening before you got a fracture. Is that correct? I mean, is that how you interpret it?

A: I don't know exactly the meaning of this part of the curves, of the curve. I hope...

Q: Okay. In a lot of materials, this type of phenomena can occur right before fractures and I was wondering whether you had thought about this as to its relationship to the material properties associated with the ribs?

A: I'm sorry.

Q: That's okay. No problem.

A: Thank you.

Q: But in this case, this is a stiffening and what you'd be describing might be a softening.

A: No, not necessarily because it's in adjacent rib fractures, then the rib that you're looking at could take up a greater percentage of the strain or load. So …

Q: It could take up a greater percentage of the load, but what you're saying is the loading rate, then, increases cause that's what happened?

A: The strain rate could…Both the rate and the load, yes.

Q: Because in this case, you're quickly increasing the strain so you'd say the loading rate, because of an adjacent failure.

A: You've got an adjacent failure.

Q: I see. So it may or may not be a material fracture.

A: It may or may not be material.

Q: Okay. Thank you.

A: Well, that's my opinion. Pascal will test it.