Energy absorption of a mobile intensive care unit fixture

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Energy absorption of a Mobile Intensive Care Unit fixture

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Traineeship report

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Eindhoven, July, 2006
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1. Introduction

For the transportation of patients between intensive care departments of different hospitals a new type of ambulance bed is developed. This bed is developed by the University Hospital of Maastricht together with the Eindhoven University of Technical. The new bed will be able to carry all the medical equipment that is present at a pediatric intensive care unit (PICU) and the patient so that it is easy to handle and as safe as possible. This bed will be called the Mobile Intensive Care Unit (MICU). In this report the construction of the MICU will not be treated. For this there will be referred to literature [1]. In this report there will be looked at the fixation of de MICU in the ambulance and specifically to the crash safety and energy absorption during a crash of the ambulance. There will treated an analytical calculation and also a static and a dynamic test of the energy absorption and the crashworthiness of the fixation between the MICU and the ambulance. The static test is done on a tensile testing machine and the dynamic test is carried out in a crash test.

In this report there will also be a design for the same sort of fixture in the ambulance but then for a stretcher that is a bit lighter than the MICU.

As specification of the MICU, there is that the MICU must be crashworthy till 20 g and this with a total mass of MICU and patient of 300 kg. Further more, from construction point of view, the crumbling zone of the fixation in the ambulance may not exceed 10 cm at a crash where there acts 20 g on the MICU.
2. Assignment description

Previously there is made a design for a MICU and the fixture of the MICU in the ambulance. There is made an analytical calculation and a static test for the energy absorption of this fixture.

Before transporting patients with the MICU in ambulances, there has to be done a dynamic test which will simulate the velocities and forces that will act on the fixture during a real crash to see if the fixture can absorb enough energy and to see if the principle of the fixture works and for this test there also has to be made a test set-up and before testing there has to be looked at the dynamic affects of strain.

There is also asked to design a fixture that is suitable to fixate a regular ambulance bed in an ambulance.
3. Design of the fixture

3.1 Fixation of the MICU in the ambulance

When a MICU is in the ambulance, it will be held in place by 4 pins that come out of the MICU and go into a specially designed absorption fixture that is mounted in the ambulance just under the MICU.

The mounting works as follows: The pin is mounted in the MICU (D). Pushing the plunger (A) downwards will result in a downward movement of the plunger (A) and the tube (B) which are connected to each other by a spring (C). When the tube hits the bottom of the rectangular tube, it stops and the plunger will move a bit further and push the balls (E) outwards in a chamber in the hammer (F). The pin will be locked in place and the balls prevent movement in the z direction. When the pin is unlocked, the plunger can move upwards again. Because there is a slope at the top of the camber in the hammer, the balls will move inwards and the whole pin can be taken out of the fixture.
The hammer is mounted in a rectangular tube as can be seen in figure 2.

During a hard crash, the hammer where de MICU is attached to, will move forwards and it will deform strip (I) into the shape of strip (J). This way, the MICU has a longer brake path and the forces on the medical equipment and the patient will be smaller. To minimize the forces that act on the fixture, they will be mounted as far as possible from each other and the distance between the MICU and the hammer will be as small as possible. Therefore the fixture will be mounted as can be seen in figure 3, so the fixture is as far as possible to the outer edge of the MICU and close to the undercarriage of the MICU.
3.2 Energy absorption of the deformation strip

When there is a crash at the front or the rear of the ambulance, a deformation strip between the MICU and the ambulance will deform plastically. This way the MICU has some extra stopping distance. Due to the longer stopping distance, the time in which the crash is taking place will be longer and therefore the deceleration becomes smaller, so the forces that act on the MICU and the patient will be smaller too. The energy that must be absorbed by the deformation strip can be calculated with formula 1.

\[
E_{abs} = m \cdot a \cdot s = 1500 \text{[J]} \quad [1]
\]

\[
m = 75 \quad \text{[kg]} \quad \text{(mass per fixture)}
\]
\[
a = 200 \quad \text{[m/s}^2] \quad \text{(deceleration at 20 g)}
\]
\[
s = 0.1 \quad \text{[m]} \quad \text{(deformation length)}
\]

During a crash the hammer will move with respect to the rectangular tube. This is made possible by the deformation strip that will change shape as can be seen in figure 4.

![Figure 4: Deformation strip before (a) and after (b) a crash](image)

The energy that can be absorbed by this strip can be calculated with formula 2. The derivation of this formula can be found in appendix G of literature [1].

\[
E_{abs} = 2\sigma_y b s \left( \frac{T^2 - kT^2 + k^2 T^2}{R + kT} \right) + \varepsilon_{el,max}^2 \left( R + kT \right) - \varepsilon_{el,max} T \quad [2]
\]

\[
E_{abs} = 1500 \text{[J]} \quad \text{(energy)}
\]
\[
s = 0.1 \quad \text{[m]} \quad \text{(deformation length)}
\]
\[
T = 3 \quad \text{[mm]} \quad \text{(thickness of the strip)}
\]
\[
R = 3 \quad \text{[mm]} \quad \text{(inner radius of the bending)}
\]
\[
k = 0.33 \quad \text{[-]} \quad \text{(neutral line)}
\]
\[
\sigma_y = 340 \quad \text{[N/mm}^2] \quad \text{(yielding stress)}
\]
\[
\varepsilon_{el,max} = 0.001 \quad \text{[-]} \quad \text{(maximum elastic strain)}
\]
\[
b = 35.2 \quad \text{[mm]}
\]
4. Static test

To check formula 2 about the energy absorption there is done a static push test on a tensile test machine where the deformation strip is deformed in such a way that will happen in the rectangular tube in an ambulance. For this test there have been made 5 strips that were 3 mm thick and 32 mm wide and which were deformed plastically over a distance of 100 mm. The calculated force that is needed to deform this strip is 13.6 kN. The deformation speed, at which the test was taken place, varies between 10 till 40 mm/min. For these speeds there can still be talked about static testing, because the speeds are much lower then the deformation speed of the strip during a crash.

<table>
<thead>
<tr>
<th>Number</th>
<th>Deformation speed [mm/min]</th>
<th>Preload [N]</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>50</td>
<td>Stress-relieve by annealing (6h, 600°C)</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

Although statistic certainty cannot be reached from a test with 5 strips, we may conclude that a force of about 14.5 kN is needed to deform the strip. The energy that is dissipated is the surface under the lines of figure 5 and this is roughly $14.5 \cdot 0.1 = 1.45$ kJ. So the analytical solution has a little error compared to the static test, but because a strip with a width of 32 absorb 1.45 kJ in a static test and it is fits good in a rectangular tube 60x40x3 there is chosen for this strip as deformation strip in the fixture.
5. Dynamic test

5.1 Strain rate sensitivity

It is widely observed that metals are strain rate sensitive. The higher the strain rate is the more force is needed to deform the metal. For this reason there will be done a dynamic test for the energy adsorption of the deformation strip. Due to the fact that the material has a higher yield stress at higher strain rates, the deformation strip can absorb more energy in the same deformation path for which it is designed. So the strip can absorb probably more energy than the 1.45 kJ.

The ratio between the dynamic force and the static force with relation to the strain rate is given in formula 3.

\[
\frac{F_{\text{dyn}}}{F_{\text{stat}}} = 1 + \left( \frac{\dot{\varepsilon}}{D} \right)^{\frac{1}{p}}
\]

\[ D \text{ and } p = \text{strain rate parameters.} \]
\[ \dot{\varepsilon} = \text{strain rate} \]

It is very difficult to find the right strain rate parameters, because strain rate sensitivity for large deformations is ignored in almost all theoretical and numerical methods, largely because so little reliable data exists. It is known that hot rolled, mild steel can have a dynamic force that can be twice as high as the static force for high strain rates and that some aluminium alloys are almost insensitive for the strain rate. There have been made some assumptions for strain rate parameters. In the book of W. Witteman [3] there has been made a assumption for the strain rate parameters for the material FeP03

![Dynamic behaviour](image)

figure 6: strain rate sensitivity for FeP03, \( p=10 \) and \( D = 1300 \)
As can be seen in figure 6, the ratio between dynamic and static force will increase with increasing strain rate. The strain rate varies over the thickness of the strip. This is due to the rolling of the bending in de deformation strip. During a crash the strip will be bend over a radius of 3 mm and than bend back after 180°. In the bend there is a line, the neutral line, in which the fibbers don’t stretch. The further the fibbers are from the neutral line, the more the fibbers are stretched or compressed.

\[ L_{\text{max}} = \frac{\alpha}{360} 2\pi (R + T) \]

\[ L_{\text{b}} = \frac{\alpha}{360} 2\pi (R + kT) \]

\[ L_{\text{min}} = \frac{\alpha}{360} 2\pi (R) \]

**figure 7: strain in the bending**

There will be assumed that the strain rate sensitivity is equal for stretching as for compressing and with this assumption the total strain can be obtained by the sum of the stretched and compressed strain.

The average strain in the martial during the bending can be calculated with formula 4

\[ \varepsilon_{\text{ave}} = \int |\varepsilon(y)| \, dy \]  \[ \text{[4]} \]

\[ \varepsilon_{\text{ave}} = \int_0^{kT} |\varepsilon| \, dy + \int_{kT}^T |\varepsilon| \, dy \]  \[ \text{[5]} \]

\[ \varepsilon_{\text{ave}} = 0.21 \]

\[ \dot{\varepsilon} = \frac{d\varepsilon}{dt} \]  \[ \text{[6]} \]

The strain rate can be calculated by the time derivative of the strain, but the time in with the strain takes place is unknown. The time depends on the velocity by which the bend is formed and the shape of the bend.

If the bending has a constant radius from the beginning of the bend, strain has to be taken place instantaneously in the first part of the bend. This means that the strain rate is infinitely high.

It is also possible that the bend is not a perfect half circle, but more a spiral shaped bend where the radius becomes smaller near the end of the bend. In that case, the time in with the bend is formed depends on the velocity and the radius of the neutral line. The velocity will become zero at the end of the crash, so the time in with the bend is formed will become large. Because of this, the strain rate will be near zero at the end of the crash.

So a good approximation for the strain rate can not be made. This means that the ratio between the dynamic and static force can not be calculated, but as can be seen in figure 6, the dynamic force will be high than the static force due to strain rate sensitivity of the material.
5.2 Dynamic test set-up

The dynamic test will be carried out in the form of a crash test. For the crash test there is a test set-up made which can be mounted on the crash test. The test set-up consists of a rectangular tube which is welded to a mounting plate. The mounting plate will be mounted on the crash test. A pin is welded in the rectangular tube and the pin will go in to the hole of the hammer that is part of the MICU fixation. The pin will represent the pin that comes out of the MICU. There is also a linear guidance mounted at the rectangular tube so the fixture will always stay on the test set-up. At the end there is welded a square tube to absorb the energy of the sledge when something went wrong with the pin or the fixture. This tube will absorb the energy of the sledge before the fixture is squished between the mounting plate and the sledge. In figure 8 and 9 you can see the part and the assembly of the test set-up.

The crash test consists of a frame on wheels with a concrete bloke, a linear guidance and a pneumatic cylinder which will propel the sledge. When the sledge is fired, the sledge moves towards the concrete bloke and due to conservation of impulse the bloke will move towards the sledge. The impact velocity is the velocity between the concrete block and the sledge and this is measured just before impact. The kinetic energy that has to be absorbed by the strip can be calculated with formula 7

\[ E_{kin} = \frac{1}{2} M' v_{crash} \]  \[7\]

\( M' \) is the virtual mass of the system and can be calculated with formula 8. The derivation of formula 8 can be found in appendix A.

\[ M' = \frac{m_1 \cdot m_2}{m_1 + m_2} \]  \[8\]
During a crash the time in which the crash takes place is important for the velocity and the mass of the sledge. The ambulance has a crumbling zone of 0.6 meter. And as said before, the MICU is fixated to the ambulance and between them is a deformation strip that can deform another 0.1 meter. During a crash the MICU must be able to withstand deceleration up to 20 g. With the crumbling zone and the maximum deceleration it is possible to calculate the speed at which the crash accrue and when this speed is know the crash time can be calculated.

\[ a = \frac{v}{t} \]  
\[ s = t \cdot \frac{v}{2} \]  
\[ v = \frac{1}{2} v \]

When rewriting and substituting formula 10 and 11 in formula 9:
\[ v = \sqrt{a \cdot 2 \cdot s} \]
\[ a = 200 \text{ [m/s}^2\text{]} \] (deceleration)  
\[ s = 0.1 \text{ [m]} \] (deformation length)

\[ v = 16.73 \text{ m/s} = 60.2 \text{ km/h} \]

Substituting formula 10 in 11, it is possible to calculate the crash time of 0.072 sec. In this time the MICU has to travel 0.1 meter, what means a velocity relatively to the ambulance of 2.8 m/s at the beginning of the crash and 0 m/s at the end. The amount of energy that has to be dissipated is known and the velocity is known. The mass of the sledge can now be calculated with the formula for kinetic energy of a moving mass.

\[ M' = \frac{2 \cdot 1500}{2.8^2} = \frac{m_1 \cdot m_2}{m_1 + m_2} = 385 \text{ kg} \]

\[ m_1 \text{ and } m_2 \text{ are the masses of the structure and the sledge. The mass of the structure is 2500 kg. If this is substituted in formula 8, the mass of the sledge can be calculated and will be 454 kg. The sledge however consists of basic structure of 220 kg where extra mass can be added in the form of 20 or 180 kg. So for the test, the sledge will be provided with an extra mass of 180 kg to a total mass of 400 kg.} \]
5.3 Test results

The test is carried out two times with the same fixture but in opposite direction, so both deformation strips in the fixture will be deformed. The arrival speed of the sledge at the time of collision for the first test is 2.75 m/s. For the second test the speed of the sledge is slightly higher to 2.96 m/s. The force that is acting on the fixation is measured by 3 pressure sensors between the test set-up and a concrete block behind it. In figure 10 you can see the forces on the fixation during the crash.

![Figure 10: Forces on the fixation during the crash test](image)

<table>
<thead>
<tr>
<th></th>
<th>test 1</th>
<th>test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [J]</td>
<td>1300</td>
<td>1510</td>
</tr>
<tr>
<td>Crash velocity [m/s]</td>
<td>2.75</td>
<td>2.96</td>
</tr>
<tr>
<td>Deformation length [mm]</td>
<td>86.6</td>
<td>91.0</td>
</tr>
</tbody>
</table>

The forces that are measured during the crash test are rather low in comparison with the static forces of 14.5 kN that was necessary for the static test. Especially the first test gives a low force.

If you look at the energy that has to be absorbed and the deformation length than there is a better fit with the predictions. The fixture is designed to absorb 1.5 kJ in 100 mm of deformation strip. There have been done two crash tests so statistic certainty cannot be reached and both test results give different dynamic forces.

What the crash tests give us is that the principle of the fixture works during a crash, but when you want statistic certainty for the deformation due to crashes, there has to be made more tests.
6. Fixation of a regular ambulance bed in an ambulance

As so far there is only looked at a fixture of the MICU to an ambulance, but this mechanism is also very useful for a regular ambulance bed like a stretcher. The only difference that must be kept in mind is that the weight of a stretcher with a patient will be less than a MICU with equipment and a patient. A stretcher is designed to carry patient up to 200 kg. The deformation strip will be designed to deform 100 mm for a crash of 20 g and a patient of 120 kg. There is been chosen for a patient of 120 kg in stead of 200 kg, because if the fixture is designed for a 200 kg person, the deformation strips will be much to stiff for the majority of the patients. However, a stretcher is designed to withstand patients up to 200 kg and so the fixture must be able to hold this amount of mass during a crash. So the deformation strip has to deform 100 mm during a heavy crash with a patient of 120 kg and for patient up to 200 kg the deformation must be a little bit bigger. This will be done by making a slot in the rectangular tube in which the pin can move 100 mm forwards and backwards. If a heavier patient has a crash with deceleration up to 20 g, the pin reaches the end of the slot and go trough the tube which will be rated open as can be seen in figure 11. So after the deformation strip is deformed 100 mm the force that is needed to displace the hammer further is increased due to the combined forces that are needed to deform the strip and to tare open the tube.

figure11: Deformation at the end of the slot
The energy that has to be absorbed by the deformation strip can be calculated with formula 1.

\[ E_{\text{abs}} = m \cdot a \cdot s = 750 \, [\text{J}] \]  

- \( m = 37.5 \, [\text{kg}] \)  
- \( a = 200 \, [\text{m/s}^2] \)  
- \( s = 0.1 \, [\text{m}] \)

The width of the deformation strip for the MICU is 32 mm and is designed for an energy dissipation of 1500 J. The energy absorption is linear dependent on the width of the strip as can be seen in formula 2. So to absorb a kinetic energy of 750 J, the strip has to have a width of: \( \frac{750}{1500} \cdot 32 = 16 \, [\text{mm}] \)

From construction point of view it will be practical to make the strip 18 mm wide. This way there is an easy fit in extruded aluminium rectangular tube 60x25x3. There is chosen for an extruded aluminium tube because these kind of tubes has sharp edges and therefore the deformation strips don’t have to be rounded of to fit in the tube. The strip can be fixed in the tube by rivets. This way the strip can be replaced after a crash by removing the rivets.
7. Conclusion and recommendations

There has been made a design for a fixture of a Mobile Intensive Care Unit in an ambulance that will deform during a frontal crash or a crash in the rear. The design is based on a strip that will deform during a crash. The dimension of the strip is calculated analytical. There has been done a static test to check the analytical calculation. This had the result that the strip could be a bit smaller. For this internship there is made a dynamic test in which there is looked if the design works and what the influence of the dynamics are like strain rate. The result of this was that the design works and that the energy that was absorbed during deformation also was good. The strange thin was that the forces that were measured during the first test were low for which there is no logical explanation. Further more, this design of the fixation can also been used to fixate regular ambulance beds in ambulances for which there is made a design.

Recommendations:

- For statistic certainty of energy absorption during a crash, there has to be done more tests.
- Check the dynamic forces with another test.
- Use this design of fixture also to fixate regular ambulance beds in ambulances so the forces on the stretcher and patient will be lower during a crash.
Test of fixation between MICU and ambulance

Literature list


Appendix A
Tijdens een botsing tussen botsmassa en een barrière wordt aan de wet van behoud van impuls voldaan. Na afloop van de botsing hebben de barrière en de botsmassa dezelfde snelheid. De wet behoud van impuls, welke algemeen geldt bij een botsing tussen lichamen, luidt:

\[(m \cdot v)_{\text{voor botsing}} = (m \cdot v)_{\text{na botsing}}\]

\[(m_{\text{botsmassa}} \cdot v_{\text{botsmassa}} + m_{\text{barrière}} \cdot v_{\text{barrière}})_{\text{voor}} = ((m_{\text{botsmassa}} + m_{\text{barrière}}) \cdot v_{\text{barrière}})_{\text{na}}\]

In figuur 1 zijn ook de gebruikte symbolen voor de verschillende fysische objecten aan gegeven. Voor de duidelijkheid hieronder een opsomming van de verschillende symbolen.

- \(m_1\) = Massa van de botsmassa
- \(m_2\) = Massa van de barrière
- \(x_1 / v_1 / a_1\) = Verplaatsing/Snelheid/Versnelling van de botsmassa t.o.v. de vaste wereld
- \(x_2 / v_2 / a_2\) = Verplaatsing/Snelheid/Versnelling van de barrière t.o.v. de vaste wereld
- \(F_p\) = Kracht uitgeoefend op het proefstuk
- \(F_a\) = Kracht die wordt uitgeoefend door de aandrijving

De botssnelheid is nu gelijk aan het verschil in snelheid tussen botsmassa en barrière. Hierbij moet wel rekening gehouden worden met de richting van de snelheden.

\[v_{\text{bots}} = v_1 + v_2\]

Uitgaande van stilstand geldt na het aandrijven van de botsmassa via de impuls-wet:

\[\left( (m_{\text{botsmassa}} \cdot v_{\text{botsmassa}} + m_{\text{barrière}} \cdot v_{\text{barrière}})_{\text{voor botsing}} \right)_{\text{na botsing}} = 0\]

\[\left( (m_1 \cdot v_1) + (m_2 \cdot v_2) \right)_{\text{voor botsing}} = 0\]
Uitgaande van volledige plastische vervorming staan na de botsing zowel de barrière als de botsmassa stil. De botsnelheid is dan gelijk aan:

\[
\frac{v_2}{v_1} = \frac{m_1 + m_2}{m_2} \cdot \frac{v_1}{v_2}
\]

De energie die door het testobject moet worden geabsorbeerd wordt hiermee gelijk aan:

\[
E_{kin} = \frac{1}{2} m_1 \cdot (v_1)^2 + \frac{1}{2} m_2 \cdot (v_2)^2 = \frac{1}{2} M' \cdot (v_{bots})^2
\]

Deze formule verder uitwerken leidt tot:

\[
E_{kin} = \frac{1}{2} \cdot \frac{m_1 \cdot m_2}{m_1 + m_2} \cdot (v_{bots})^2 = \frac{1}{2} M' \cdot (v_{bots})^2
\]

In deze formule is het symbool M’ geïntroduceerd. M’ is het symbool voor de virtuele massa. Het resultaat van een test op de hiervoor beschreven opstelling (zie figuur 1) is ongeveer gelijk aan een test met een botsmassa gelijk aan de virtuele massa (M’) tegen een stilstaande barrière met een oneindige massa (zie figuur 2).

---

**Figuur 2:** Conventionele testopstelling