Wood-steel structure for roadside safety barriers

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Abstract:

Some roadside safety barriers are made of a mixed steel-wood structure. This kind of structure is currently in fashion in rural places where safety equipment is meant to fit the surrounding landscape (countryside, mountains). According to the European legislation, any vehicle restraint system has to pass two crash tests compliant with the EN 1317. Our aim in the present study is to develop a dynamic model of the multi-material structure in order to understand and optimize such safety barriers i.e. to define the best possible association combining the mechanical properties of both materials (steel and wood). In our paper we will present three-point bending experimental tests made at different energy levels. The laboratory tests we carried out have served as a basis for drawing up a material constitutive law in a numerical parametric study.

Keywords: Road Equipment, Crash tests, Finite Element model, Wood-steel structure, LS-Dyna
Notation:

**ASI**: Acceleration Severity Index

Acceleration Severity Index from real test data. The ASI index is intended to give a measure of the severity of the motion for a person within a vehicle during an impact with a road restraint system. It’s a non dimensional quantity computed using the following equation (1):

\[
ASI = \max \left( \sqrt{\left( \frac{\bar{a}_x(t)}{12} \right)^2 + \left( \frac{\bar{a}_y(t)}{9} \right)^2 + \left( \frac{\bar{a}_z(t)}{10} \right)^2} \right) \tag{1}
\]

Where

\[
\bar{a}_{x,y,z} = \frac{1}{\delta} \int_{t}^{t+\delta} a_{x,y,z} \, dt \quad \tag{2}
\]

(2) represents the 3 components of the vehicle acceleration averaged over a moving time interval \( \delta = 0.05 \) s.

**W**: Working Width

The Working width is the distance between the traffic face of the non deformed restraint system and the maximum dynamic lateral position of any major part of the system during the crash (see Figure 1).

**Dm**: Dynamic deflexion

The dynamic deflexion is the maximum lateral dynamic displacement of the side facing the traffic of the restraint system.

![Figure 1: Working Width and dynamic deflection definition](image)

**Mean value**

\[
\mu = \frac{\sum X}{N}
\]

Standing \( X \) for the score and \( N \) the number of scores in the set of data.

**Standard deviation**

\[
\sigma = \sqrt{\frac{\sum X^2}{N} - \mu^2}
\]

The standard deviation is the square root of the variance. It is the most commonly used measure of spread.

An important attribute of the standard deviation as a measure of spread is that if the mean and standard deviation of a normal distribution are known, it is possible to compute the percentile rank associated with any given score.

**Coefficient of variation**

\[
CV = \frac{\sigma}{\mu}
\]

Coefficient of variation is a measure of dispersion of a probability distribution. It is defined as the ratio of the standard deviation to the mean.

The coefficient of variation is a dimensionless number that allows comparison of the variation of populations that have significantly different mean values. It is often reported as on a scale of 0 to 100% by multiplying the above calculation by 100.
European road restraint systems are evaluated within the frame of EN 1317 [1,2]. Under normal circumstances two crash-tests are to be performed:
- A first one with a light vehicle (about 900kg) so as to assess the severity of the device
- Another one with a heavy vehicle (from 1100 kg up to 38 t) depending on the restraint level in order to assess the working width (see Figure 1). As an example in the case of a N2 restraint level – normal level – in which we can find most of the steel-wood restraint systems- the heavy vehicle would be a 1500 kg car driving at a speed of 110 kmph.

It is commonly accepted that steel-wood devices have an aesthetic interest and are therefore being used mostly in places where infrastructure has to be discreet and well-integrated in the surrounding landscape (mountains, countryside). Nevertheless if we focus on the N2 level devices it is worth noticing that there are indeed significant differences between the various types of devices as illustrated in Figure 2.

![Figure 2: N2 devices statistics from LIER test database](image)

Clearly concrete devices are characterized by important values as regards the severity indices on the one hand, and by low values of deflection on the other hand. (Very few results are presented here as concrete devices are tested mainly at higher containment levels)

The differences between steel products and wood-steel products are of smaller size. It seems that products including wood are generally less aggressive (lower value regarding the severity index) but the working width is usually bigger, which is not necessarily a good selling point.

The aim of our study is to apprehend better the possible use of wood in roadside safety barriers and hopefully, to optimize its use and overcome the aesthetic point of view.

To achieve this objective, a validated numerical tool is needed. The use of Finite Elements (F.E.) models in roadside safety research is now largely adopted [3]. The capability of these models to reproduce with accuracy real crashes have been illustrated [4, 5, 6, 7, 8]. More and more, one call on FE analysis to design new devices, to understand the behaviour of existing ones, or to predict the behaviour in several conditions [9, 10, 11, 12, 13, 14, 15, 16, and 17]

In order to assess the accuracy of a multi-material numerical model, we decided to set up experimental laboratory tests.
THREE-POINT BENDING EXPERIMENTAL TESTS

Wood structures responses under dynamic loading have not been investigated a lot. A large amount of data concerning elastic characteristics is available in the literature. [18]
In order to enhance the accuracy of our finite element model, experimental tests are required. Our concept is to have a simple test configuration with energy levels comparing with those observed in real crash tests, using wooden samples of similar geometrical and mechanical characteristics.

**Tests set-up**

Tests were performed at INRETS catapult with a two-ton bogie. The different elements of the two-meter-long structure are just supported by steel posts at the front of two concrete blocks fixed rigidly and distant of 1.7 meter from one another.

![Figure 3: Tests set-up](image)

The acceleration data of the bogie and the contact forces were recorded during the tests.

**Test matrix and samples**

We decided to test two kinds of structure, wood on the one hand, and an assembly of steel and wood on the other hand (as illustrated in Figure 4). Three levels of energy were chosen and each configuration was tested three times to assess the repeatability of the process.

A total of 18 tests were performed following the above Design of Experiment:

<table>
<thead>
<tr>
<th>Speed \ Structure</th>
<th>Wood</th>
<th>Steel-Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kmph</td>
<td>3 tests</td>
<td>3 tests</td>
</tr>
<tr>
<td>10 kmph</td>
<td>3 tests</td>
<td>3 tests</td>
</tr>
<tr>
<td>20 kmph</td>
<td>3 tests</td>
<td>3 tests</td>
</tr>
</tbody>
</table>

*Table 1: Test matrix*
A total of twenty wood beams were received from a roadside safety system producer. The samples received are supposed to be fit for regular conditions of use. For steel-wood sample tests, a five-millimetre thickness steel reinforcement is fixed to the wood beam by use of two M16 bolts. Special care was taken to the mass and moisture contents of each sample. The moisture content was recorded at three points along the wood sample.

Figure 5 clearly shows that no correlation was found between moisture content measurements and the total mass of the samples. The spread of mass and moisture contents gives an indication of the heterogeneity of the wooden material.

Results

During the test, acceleration data for the bogie was recorded as well as forces (via load cells placed between supports and concrete units) with a data acquisition system of 10,000 Hz. The test area was also covered by two high speed cameras (1000 fps).
This paper presents and analyses only the acceleration data.
At the lowest level of energy (a two-ton bogie with an impact speed of 5 km/h) none of the samples failed. The answers for both structures are very similar and are characterized by a common single deceleration profile as shown in Figure 6. Even if this test configuration can be considered to be far from real roadside safety system crash test, it is worth noticing that in the absence of failure (which is the standard for roadside safety systems) there is no significant effect of the steel reinforcement.

One can see from the Figure 7 that only one sample did not fail at higher level of energy. The curve is presented in a dashed black line. This result being very different from all the other ones, it will not be taken into account either for the calculation of the experimental corridors or for the average deceleration pick value.

The differences between the two kinds of structures tested appear after the failure. In Figure 7 & Figure 8, the deceleration slope (A) is the same for all samples. Wood samples are characterized by a single pick deceleration which leads to failure (B). Steel-wood samples are marked by:
- Higher picks at posterior time values
- A deceleration plateau (C) that takes place after the failure of the wooden part and which is due to the plastic deformation of the steel reinforcement.
Curves are set to zero D to avoid a deceleration profile incurring from the breaking of the bogie.

The test results are shown in the Table 2 below each criteria being taken into consideration separately.
The bogie speed itself is very well monitored since the mean value of the coefficient of variation for the speed parameter is 1%. As regards sample mass and room temperature, the mean values of the coefficients of variation are 4% but this is still acceptable.

On the other hand, as regards moisture content, its value goes up to 28%. Furthermore the variation of the latter is very much in correlation with the variation of the result values. In Table 2, the most important values of variation of moisture content (36% and 42%) can be linked to the largest variation of deceleration pick values (respectively minus 16% and minus 14%).
The aim is to have a simple model with an element size which might be applicable to a full restraint system modelling (100 meters approximately). Moreover crash tests against roadside safety barriers usually mean high end times (more than 1 s) which lead us to a persistent search for a compromise between mesh refining and total number of elements.

For wood modelling, we use the MAT_WOOD (type 143 available in Ls-Dyna). This model, developed by Murray [19] under contract from the FHWA, consists in a transversely isotropic material. Our interests is that default material properties for yellow pine are available and temperature and moisture content could be changed (0°C - 10°C - 20°C - 30°C and 0% - 10% - 20% -30% respectively).

A parametric study was performed with “Pine” default properties at two different temperatures (20°C & 30°C) and two moisture content levels (20% & 30%) which enclose the experimental values.

Thus, for both structures at each velocity, four shots were run with Ls-Dyna explicit solver [20, 21] and compared to the real test corridors which were built by computing the mean value plus or minus its standard variation.
Results at 5 kmph

Figure 10: Wood results at 5 kmph

Figure 11: Steel-wood results at 5 kmph

Results at 10 kmph

Figure 12: Wood results at 10 kmph

Figure 13: Steel-wood results at 10 kmph

Results at 20 kmph

Figure 14: Wood results at 20 kmph

Figure 15: Steel-wood results at 20 kmph
Table 3: Failure modes comparison

<table>
<thead>
<tr>
<th>Target Speed [kmph]</th>
<th>Wood</th>
<th>Steel-wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kmph</td>
<td><img src="5kmph.png" alt="Image" /></td>
<td><img src="5kmph.png" alt="Image" /></td>
</tr>
<tr>
<td>10 kmph</td>
<td><img src="10kmph.png" alt="Image" /></td>
<td><img src="10kmph.png" alt="Image" /></td>
</tr>
<tr>
<td>20 kmph</td>
<td><img src="20kmph.png" alt="Image" /></td>
<td><img src="20kmph.png" alt="Image" /></td>
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</tbody>
</table>

Table 4: Qualitative analysis

<table>
<thead>
<tr>
<th>Target Speed [kmph]</th>
<th>Deceleration value [m.s⁻²]</th>
<th>Results</th>
<th>Numerical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wood</td>
<td>steel-wood</td>
<td>wood</td>
</tr>
<tr>
<td>5 kmph</td>
<td>-36.0</td>
<td>-39.2</td>
<td>-37.6</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>-7%</td>
<td>-4%</td>
<td>-4%</td>
</tr>
<tr>
<td>10 kmph</td>
<td>-32.7</td>
<td>-41.2</td>
<td>-25.7</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>5.8</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>-10%</td>
<td>-14%</td>
<td>-10%</td>
</tr>
<tr>
<td>20 kmph</td>
<td>-22.0</td>
<td>-30.7</td>
<td>-23.4</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>5.0</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>-9%</td>
<td>-16%</td>
<td>-12%</td>
</tr>
</tbody>
</table>

First of all, let us notice (as shows Table 3) that our multi-material model reflects perfectly the failure modes observed all along the experiments.

Moreover, the results presented in Table 4 indicate that the parametric study performed give results with the same order of spread as the experiments.

As regards acceleration data, Figure 10 and Figure 11, which correspond to the tests performed at 5 kmph, indicate that the curves obtained with the numerical model drift away from the experimental corridor at an early stage. This may be explained by the local erosion of the contact area that brings about a loss of contact. At this low velocity, it takes a long time to the bogie to find contact again.

At higher velocities (Figure 12 to Figure 15) this phenomenon is less sensitive due to the fact that erosion occurs mostly on the rear side of the beam and drives the failure mode of the structure.
Conclusion

The three-point bending experimental tests were performed at three different velocities on some samples of structure comparable to those used in certain roadside safety barriers.

Two kinds of wooden structures—with and without steel reinforcement—were tested.

A finite element model was built and a numerical parametric study using default values of the wooden material database of Ls-Dyna was performed.

The experimental results’ spread is mostly due to the heterogeneity of the wooden material. This spread is well reproduced by the numerical parametric study making temperature and moisture contents of wood vary within the frame of experimental values.

The multi-material modelling is able to reproduce the failure modes of both structures at every velocity level and gives acceleration data of good accuracy and even more so at high energy level.

This first set of results is encouraging and let us hopes that the coupling of the two materials may be optimized since, in this particular test configuration, steel acts only after wood failure, which is not expected in normal applications of roadside safety barriers.

The next step of our study will be to adapt our multi-material model to a complete structure of roadside safety system and compare it to real crash tests results.

REFERENCES