

IMPROVED THORAX BEHAVIOUR OF THE EUROSID AND EFFECTS ON THORAX INJURY ASSESSMENT, ON THE BASIS OF PENDULUM IMPACTS

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ABSTRACT

In 1989, the EUROSID-1 was accepted in the European regulation ECE-R95. After a steady period of use, an upgraded version of this dummy: ES-2 is now considered as a step towards harmonization of side impact occupant regulations. The upgrades to the dummy include, amongst others, a modification of its torso back plate and a change in rib module guidance (piston-cylinder), especially to overcome anomalous rib deflection responses referred to as “flat-top”.

Presented here are results of lateral and oblique pendulum tests, conducted on the EUROSID-1 and ES-2 to verify the modified torso back plate and to study the responses of three proposed rib module designs for ES-2. Particularly, rib deflections, rib VC responses, and thorax force-deflection responses are analyzed.

The current study primarily addresses sensitivity of the ES-2 thorax to oblique loading. The risk of anomalous rib deflection responses as observed in full-scale vehicle crash tests can be greatly reduced by using a modified torso back plate and by changing the piston-cylinder. Results presented here show that the prototype “needle bearing type ribs”, developed jointly by TNO and FTSS, eliminates the risk of flat-top in the pendulum test conditions employed in this study. The adoption of this rib design in ES-2 may, however, require further tuning of the damping in order to meet biofidelity requirements, such that injury risk on the basis of VC can be assessed appropriately.

INTRODUCTION

Changed Loading Conditions Have Implications for Dummy Designs

Advances in restraint system development, and changes in vehicle fleets over the last decade, have changed the approach to side impact occupant protection. The increased use of side airbag systems and other changes in vehicle designs, change the way occupants are being loaded in the event of a lateral

collision. This also has implications for the side impact crash test dummies that are being used in regulatory testing, even though these regulations have been around longer than the introduction of the first production side airbag system.

For the regulatory European Side Impact Dummy, EUROSID-1, this has resulted in a re-evaluation of the appropriateness of its thorax design for injury assessment under the changed vehicle and restraint interactions. Concerns have been expressed with regards to “flat-top” deflection responses, specifically observed in full-scale vehicle crash tests that induce oblique loading to the dummy. These concerns have coincided with the initiative for worldwide harmonization of side impact occupant protection regulations, which has resulted in a set of upgrades of the dummy. These upgrades, amongst which is the reduction of the risk of “flat-top”, have resulted in the development of the second production version EUROSID: ES-2 [1].

In 1998, Transport Canada commissioned Biokinetics and Associates and PMG Technologies to investigate possible causes for flat-top rib deflections using pendulum experiments. Part of the problem of this investigation was repeating the flat-top phenomenon under well controlled loading conditions, such as a pendulum test. Furthermore, a flat-top rib deflection response does not necessarily imply an anomaly, and if it does, it could have multiple causes. One possible cause is interference with the torso back plate. Another possible cause is binding of the piston-cylinder, which guides the rib deformation.

Summary of Torso Back Plate Evaluations

Three series of pendulum tests were conducted in 1998, particularly to address the risk of unrealistic interference of an impacting structure (e.g. the intruding door panel) with the dummy’s torso back plate [2]. Theoretically, such interference could only occur if the impacting surface would be rearward from lateral, but even in pure lateral (0 degrees) pendulum tests on the thorax of the EUROSID-1, contact between the

pendulum face and the torso back plate occurred. This was due to rotation of the dummy around its vertical axis; causing the loads to be directed more rearward and exposing the torso back plate.

As a result of the first two series of pendulum tests, a modification of the torso back plate was proposed, limiting its total width to 136 mm and rounding the edges. The proposed modifications have been adopted for the ES-2 torso back plate (see Figure 1). In addition to the reduced risk of unrealistic interference with an impacting structure, the new torso back plate is also likely to reduce unrealistic seat back interaction (“grabbing”).



Figure 1. ES-2 Torso Back Plate.

Modifying the torso back plate only, however, could not completely resolve the occurrence of anomalous rib deflection responses in oblique impacts on the EUROSID-1 thorax. Further investigation into the behaviour of the piston-cylinder of the rib modules was pertinent.

ASTC (now Denton ATD) had developed a new prototype rib guidance system, essentially replacing the sliding bearings of the piston-cylinder by linear ball bearings. ASTC had produced three rib modules for evaluation testing. First results of tests with these prototype rib modules were promising [2].

Concurrently, TNO and FTSS jointly developed two other piston-cylinder systems for the EUROSID rib modules. The first one is almost identical to the EUROSID-1, except for a coated piston shaft. The second one is a drastic re-design of the piston-cylinder, which incorporates a square cross-sectioned piston shaft running on needle bearings inside the square “cylinder”.

In 1999, Transport Canada commissioned Biokinetics and Associates and the Medical College of Wisconsin to run comparative tests on these three

different type rib modules, to assess which design best eliminates the risk of anomalous rib deflection in similar test conditions as those used to assess the torso back plate. Results of these tests are presented and analyzed in the current paper.

RIB MODULE EVALUATIONS

Materials

The ES-2 includes several improvements over the EUROSID-1 [1], but only two directly concern the thorax: the modified torso back plate (see Figure 1) and the piston-cylinder construction in the rib modules. All tests reported here are conducted with the new torso back plate. Three types of rib modules are included in the test program.

The first rib module type, developed by TNO, is essentially the same as the EUROSID-1 rib module with the exception of a coated piston to reduce friction with the sliding bearings. This rib module type is designated “coated” in the remainder of this paper, and is shown in Figure 2.

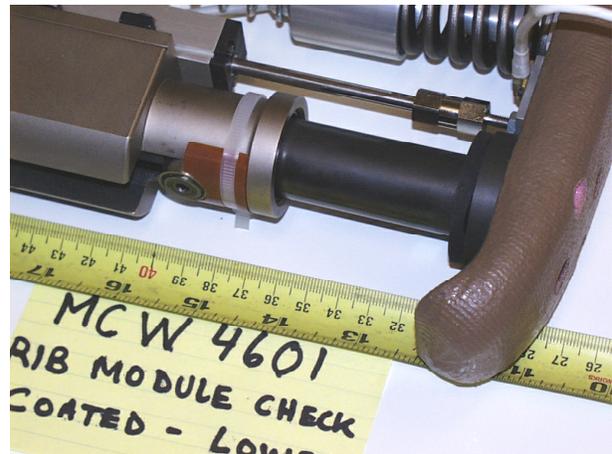


Figure 2. Piston-Cylinder Detail of the “Coated” Type Rib Module

The second rib module type, developed jointly by TNO and FTSS, incorporates a complete redesign of the piston-cylinder. A square cross-sectioned piston runs on needle bearings contained in the “cylinder”. Besides this different rib guidance, the needle bearing ribs also have a larger deflection capacity: about 60mm, depending on the final design of the rubber stop (compared to approximately 56 mm for EUROSID-1). This rib module type is designated “needle” in the remainder of this paper, and shown in Figure 3.

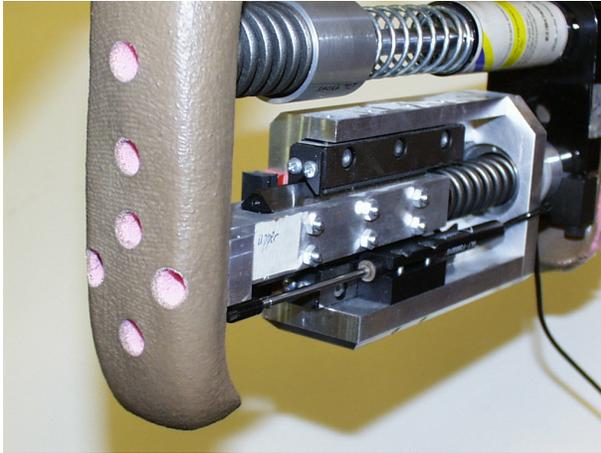


Figure 3. Piston-Cylinder Detail of the “Needle” Type Rib Module.

The third rib module type, developed by ASTC, incorporates linear ball bearings. Due to space constraints, the diameter of the piston was reduced compared to that of the EUROSID-1. Also, the linear ball bearing type rib module incorporates different rib steel, different rib foam, and a different damper, while still passing the EUROSID-1 rib module calibration specifications. This rib module type is designated “ball” in the remainder of this paper, and is shown in Figure 4.



Figure 4. Piston-Cylinder Detail of the “Ball” Type Rib Module.

In all tests, the ES-2 is equipped with three identical rib modules, so no combination of different rib modules is used.

Test Method

The test method is principally the same as previously employed to study the torso back plate

interference [2]. This pendulum test set-up, shown in Figure 5, has demonstrated a high degree of repeatability, and has allowed the reproduction of anomalous rib deflection responses (“flat-top”) with the EUROSID-1, similar to those observed in full-scale vehicle crash tests. The pendulum has a rectangular (150 mm wide by 178 mm high, 5 mm radius rounded edges), rigid (hardwood) face, which contacts only the rib modules. In all tests, the pendulum face was vertical at impact, and initial contact with all three ribs occurred simultaneously. The pendulum face is vertically centred at the mid of the middle rib. The half arm at struck side, the shoulder foam, and jacket are removed to increase visibility of the rib behaviour during impact. The pendulum face is covered with a neoprene slab, taken from a dummy jacket to compensate the absence of the jacket on the dummy as far as contact stiffness is concerned.

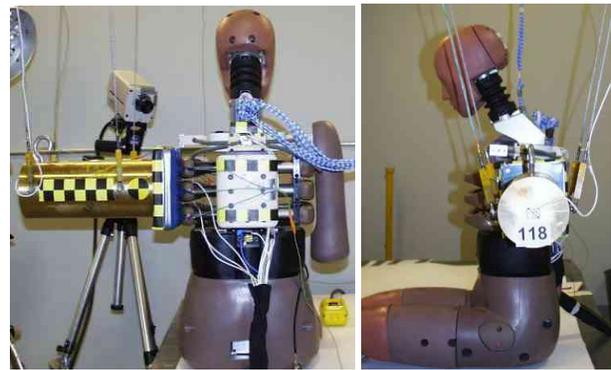


Figure 5. Pendulum Test Set-up (0 Degree Test).

The mass of the pendulum is 43.4 kg. Two impact velocities are used in the test matrix: 5.0 m/s and 6.5 m/s, providing a pendulum kinetic energy at impact of approximately 543 J and 917 J respectively.

Part of the rationale for the pendulum mass originates from the investigation of torso back plate interference [2]. For this study, a high energy impact is required to obtain rib deflections well beyond 40 mm, necessary to induce back plate interference.

Another part of the rationale for the pendulum mass comes from other studies. In the past, TNO has investigated the potential for flat-top rib deflections using lower mass pendulums (up to approximately 23.4 kg) striking an isolated rib module or a thorax assembly (without back plate). In these impacts, however, flat-top could not be reproduced [3]. Other investigators have also tried to reproduce flat-top using a pendulum or impactor set-up, but were not successful to do so in pure lateral impacts [e.g. Lau et al in 4]. The only other known successful attempt to reproduce flat-top is

reported by Radwan Samaha et al [4]. In this study, a 907.4 kg “part 581 bumper pendulum” is used, striking the shoulder, thorax, and abdomen of the dummy at approximately 5.0 m/s. Pendulum kinetic energy at impact is approximately 11300 J. Such energy directed at the thorax only, would certainly have resulted in severe damage to the rib modules, but the study does indicate that an increased pendulum mass increases the chance of reproducing flat-top.

Test Matrix

As mentioned above, the pendulum velocity is set at nominally 5.0 m/s and 6.5 m/s. Impacts are conducted at angles forward from lateral (+15 degrees and +30 degrees), pure lateral (0 degrees), and rearward from lateral (-15 degrees and -30 degrees). The study includes three different rib module types. Two tests are conducted for every combination of rib module type, impact velocity, and impact angle, to check the repeatability of the tests.

The total number of scheduled tests is 60, however, only 48 tests have actually been conducted. The ball bearing rib modules showed permanent deformation after 8 tests (0 and -15 degrees; 5.0 and 6.5 m/s) and further tests could not be conducted on these ribs. The deformation of the ball bearing ribs is most likely a result of the -15 degrees, 6.5 m/s tests, however, these particular rib modules had also been involved in previous test series at other labs.

Measurements taken for every test include pendulum velocity at impact (V), pendulum acceleration in the direction of impact (PACC), tri-axial dummy upper spine accelerations (USAX, USAY, USAZ, used to calculate the resultant USAR), tri-axial dummy lower spine accelerations (LSAX, LSAY, LSAZ, used to calculate the resultant LSAR), upper-, middle-, and lower rib deflections (URD, MRD, LRD), and uni-axial upper-, middle-, and lower rib accelerations (URA, MRA, LRA). All measurements and post-processing conform to JSAE 211, except for PACC, which is filtered at CFC180 rather than CFC60.

Results

Repeatability: For practical reasons, this paper does not include the traces for all measurements taken, but only those that are of particular interest in comparing the responses of the different types of rib modules. Repeated tests per combination of rib module type, impact velocity, and impact angle show good to excellent repeatability, which allows the analyses to be limited to 24 tests. Furthermore, the results presented in

this paper equally apply to all three rib modules of one assembly (upper, middle, and lower). Obviously, upper, middle and lower rib responses are different but they show similar trends. The responses presented below are therefore shown for only one rib: the middle rib.

Responses from 0 Degree Tests: Figure 6 and Figure 7 show a comparison of middle rib deflection (MRD) and middle rib viscous criterion (MRVC) of the three different rib modules. At 5.0 m/s the peak rib deflections are quite similar (approximately 47 to 48 mm), however, the unloading phase of the coated rib module takes much longer than that of the needle or ball rib modules. At 6.5 m/s, the needle rib module deflects to about 58 mm, while the coated rib module bottoms at about 56 mm, and the ball rib module only reaches about 50 mm deflection. Again, the unloading phase of the coated rib module takes much longer than that of the needle or ball rib modules.

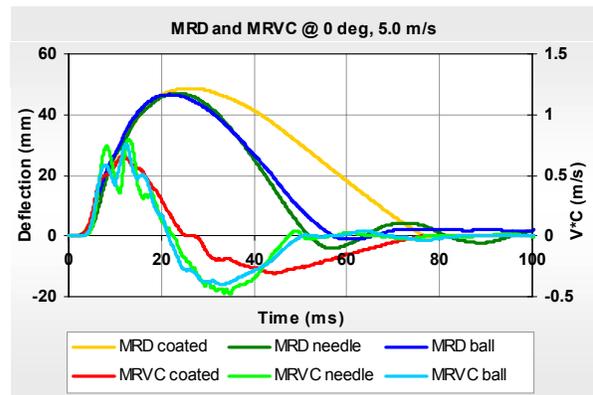


Figure 6. Middle Rib Responses @ 0 deg, 5.0 m/s.

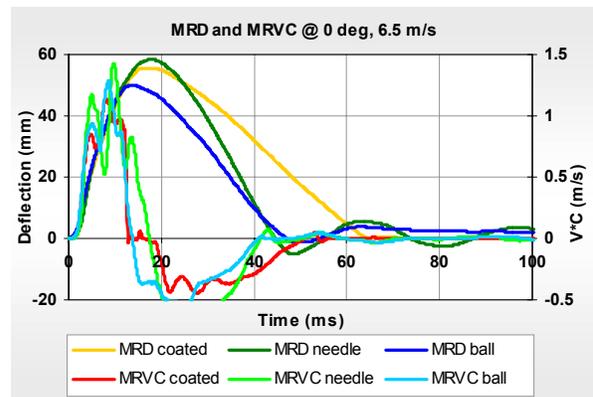


Figure 7. Middle Rib Responses @ 0 deg, 6.5 m/s.

Whereas deflection-time histories of all rib module types appear rather uni-modal, the VC calculations reveal otherwise. In both 5.0 m/s and 6.5 m/s impacts,

the VC of the coated rib module stays approximately zero for several milliseconds when maximum deflection is reached. For the 6.5 m/s impact, this is due to bottoming, however, for the 5.0 m/s impact, no bottoming occurs in the coated rib module. Also, in the 5.0 m/s impact no contact with the torso back plate occurs. The levelling of VC at zero therefore suggests a flat-top with the coated rib module at 5.0 m/s (for about 3 ms).

Such a flat-top is not detected with the needle or ball rib module types, however, considerably more oscillation in the VC-time history can be observed. This oscillation appears to be a result of the particular impact condition (and is confirmed by the oscillating rib acceleration responses, which are not presented here). The pendulum accelerates the rib cage to a higher velocity than the instantaneous pendulum velocity, since the effective rib cage mass is lower than the pendulum mass. Calculations show that the ribs are accelerated to a velocity of approximately 9.5 m/s. At such high rib velocity, the damper becomes effective and will resist the rib motion, effectively slowing it down. The pendulum will hit the rib again, and accelerates the rib again. And so forth and so on, until maximum energy transfer has occurred or the ribs bottom out.

The relatively low peak deflection of the ball rib module at 6.5 m/s is not due to flat-top (VC does not remain zero) nor to back plate contact, but is in fact a bottoming, confirmed by the relatively high upper and lower spine accelerations at the time of peak deflection.

Responses From Oblique Tests (-30, -15, +15, and +30 degrees): Figure 8 through Figure 13 show the effects of the impact angle on the middle rib deflection for 5.0 m/s and 6.5 m/s tests. Only data on 0 degree and -15 degrees tests are available for the ball type rib, due to permanent deformation of the rib and piston.

For the 5.0 m/s tests, impacts at -15 degrees result in peak deflections that are similar to those obtained in 0 degree impacts. This is true even between different rib types: peak MRD for all tests and all different rib modules are within the narrow range of 46-50 mm. Differences only become apparent at high impact velocity.

At 6.5 m/s, only the needle type rib module shows sensitivity between 0 degree and -15 degree impact angle. At this higher velocity, the coated type ribs bottom at about 56 mm. The ball type ribs bottom at approximately 50 mm, which is only a few mm higher than the 47 mm peak deflection obtained in the 0 degree tests. The ball type rib module shows the least sensitivity to impact angle and impact velocity in the test conditions used here.

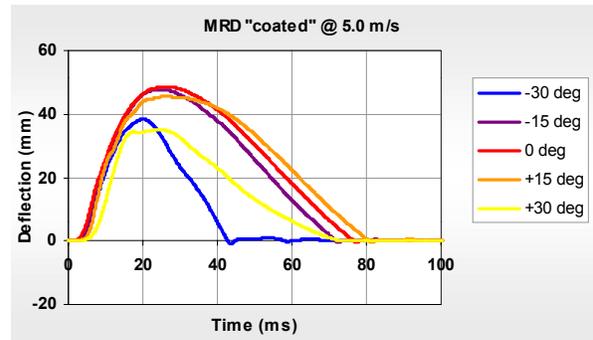


Figure 8. Coated Middle Rib Deflections @ 5.0 m/s

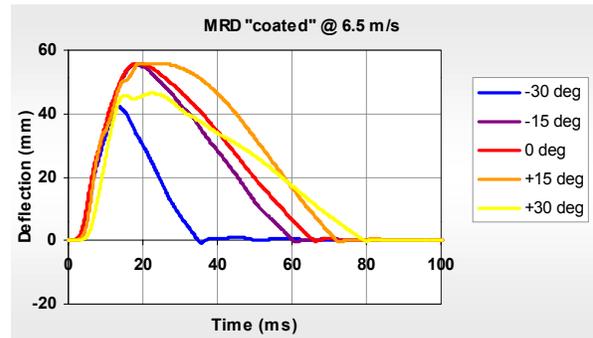


Figure 9. Coated Middle Rib Deflections @ 6.5 m/s

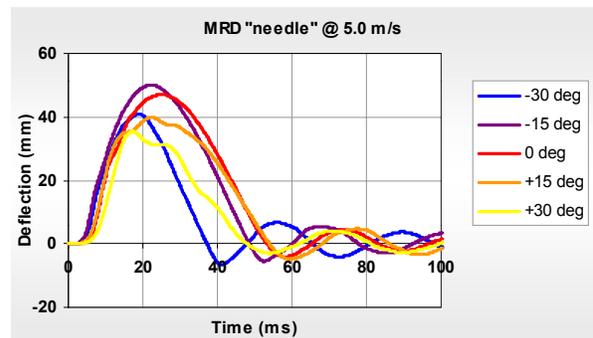


Figure 10. Needle Middle Rib Deflections @ 5.0 m/s

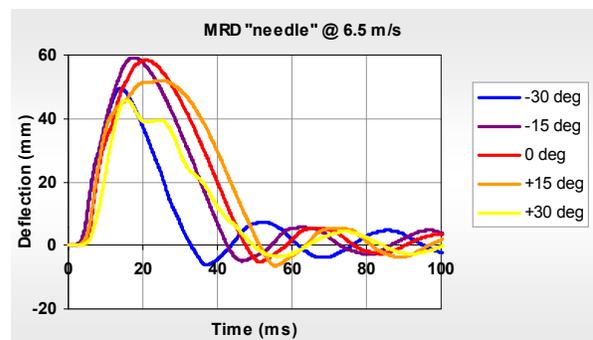


Figure 11. Needle Middle Rib Deflections @ 6.5 m/s

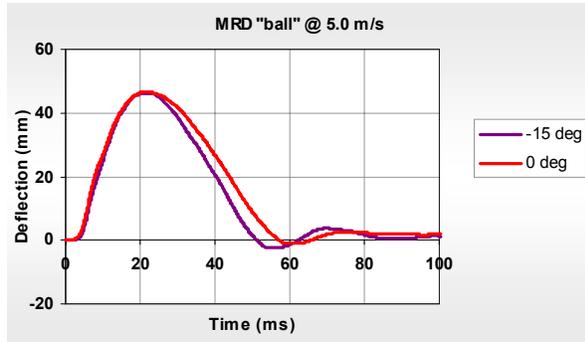


Figure 12. Ball Middle Rib Deflections @ 5.0 m/s

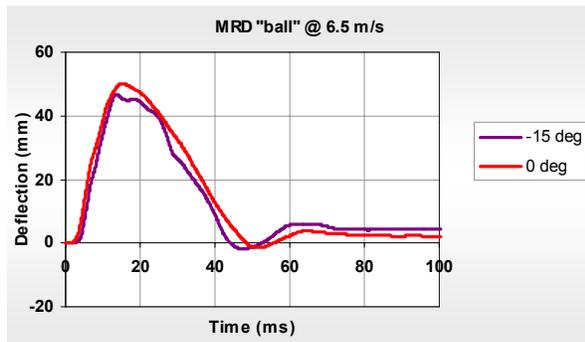


Figure 13. Ball Middle Rib Responses @ 6.5 m/s

Increasing the impact angle to -30 degrees (for the “coated” and “needle” type ribs), reduces the peak deflections considerably, shortens the time duration, and interference with the torso back plate at both 5.0 m/s and 6.5 m/s is observed (also seen as increased spine accelerations, not shown here). Despite this interference, the rib deflections do not exhibit flat-top: VC responses do not remain zero for some time at maximum rib deflection.

At $+30$ degrees impacts, rib deflections are also greatly reduced, however, time duration is similar to impacts at smaller angles (-15 , 0 , $+15$ degrees). This is probably due to a higher engagement of the damper in impacts forward from lateral. Rib deflections obtained in impacts forward from lateral ($+15$ degrees and $+30$ degrees) also exhibit the ‘oscillation’ observed in the 0 degree tests, and mostly so at $+15$ degrees since the rib deformation velocity is highest.

DISCUSSION

Any side impact dummy thorax design is a compromise between sensitivity, biofidelity, durability, repeatability, measurement capacity, and other characteristics. With the changes in side impact loading conditions happening over the last decade, design

targets for the thorax of side impact dummies have changed. Higher impact velocities are expected, particularly from airbag interactions, and better sensitivity to off-axis (oblique) loading is now desirable.

These new requirements and the potential for unrealistic dummy to seat back interaction have resulted in a re-evaluation of the EUROSID thorax design. In a previous study, unrealistic torso back plate contact has been addressed, resulting in a modified design of this component [1, 2]. The modified torso back plate reduces the risk of unrealistic interaction, although the current study indicates that at high velocity and at impacts rearward from lateral, contact may still occur. On the other hand, such contact can only occur provided the torso back plate is exposed, which is unlikely in a full-scale vehicle crash test where the dummy is positioned in a seat.

Three prototype ES-2 rib module designs are evaluated in this study under lateral and oblique pendulum loading. The major design differences between these modules concern the piston-cylinder construction, which guides the rib deformation during impact. The first prototype rib module design differs from that of the EUROSID-1 only by a coated surface of the piston. The second prototype incorporates a complete re-design of the piston-cylinder, and uses needle bearings to eliminate the risk of piston-to-cylinder binding. The third prototype incorporates linear ball bearings in the piston-cylinder in stead of the standard EUROSID-1 sliding bearings.

All three rib module designs show good to excellent repeatability. Reproducibility is not addressed in this study.

Undesirable flat-top responses are obtained with the coated type rib modules (see Figure 6 and Figure 7), which cannot have been caused by torso back plate contact or bottoming. The needle and ball bearing type rib modules do not exhibit any similar flat-top response, under the current test conditions.

The needle bearing type rib module shows the highest sensitivity to impact direction and does not exhibit flat-top.

The ball bearing type rib module shows insufficient sensitivity to the impact angle in the current test conditions, partly due to a limited deflection capacity of this rib module type.

Particularly in the -15 degrees, 0 degree, and $+15$ degrees tests, deflection responses appear uni-modal, but the VC calculations show otherwise. Due to the relatively high pendulum mass, the ribs are accelerated to a velocity higher than the pendulum velocity at impact. When this happens, the damper starts decelerating the rib until the pendulum hits the rib

again. This behaviour repeats itself several times before maximum deflection occurs, and appears as oscillations in the VC responses, which are less obvious in the deflection-time histories. This particular behaviour is further analyzed by calculating the thorax force-deflection characteristics.

Both the needle and ball bearing type rib modules show a shorter deflection pulse, than the coated type. Combined with the oscillation in the rib deflection at the end of the unloading phase (see Figure 6 and Figure 7), this indicates a different damping for the needle and ball type rib modules, compared to the coated type (or standard EUROSID-1 type).

Using the pendulum acceleration to calculate the force acting on the dummy, and calculating the average thorax deflection using URD, MRD, and LRD, force-deflection responses are obtained for the complete thorax of the ES-2. Figure 14 and Figure 15 show force-deflection curves thus obtained, for impacts at 0 degree and 5.0 m/s and 6.5 m/s.

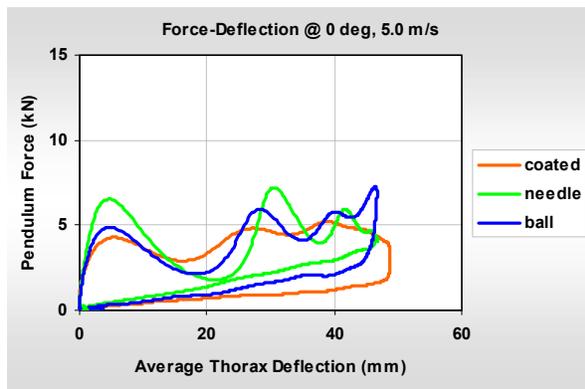


Figure 14. Thorax Force-Deflection @ 0 deg, 5.0 m/s

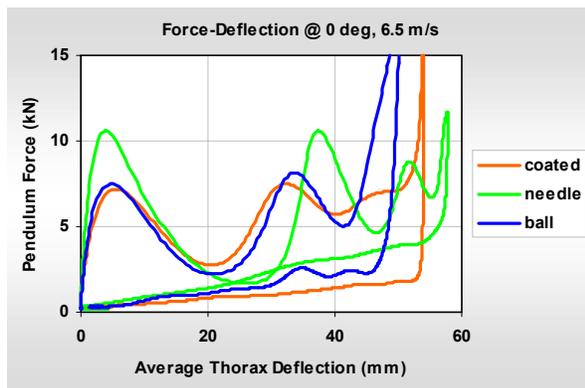


Figure 15. Thorax Force-Deflection @ 0 deg, 6.5 m/s

The force-deflection curves in Figure 14 and Figure 15 indicate that the needle and ball type rib modules exhibit less damping than the coated type rib module. The typical force-deflection curves shown here have also been observed in other studies, conducted on the EUROSID-1 at reasonably high velocities; beyond 9 m/s [5, 6]. After first contact between pendulum and thorax, the force drops considerably, thus implying continued deflection occurs with a low resistance. This kind of behaviour cannot be confirmed by biofidelity tests [5, 7]. It appears that further tuning of the thorax damping for ES-2 is required.

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DISCLAIMER

The opinions expressed here are those of the authors and do not necessarily reflect those of Transport Canada.

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