DESIGN AND EVALUATION OF AN INSTRUMENTED ABDOMEN FOR THE NHTSA ADVANCED DUMMY

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ABSTRACT

A dummy abdomen consisting of two sections was designed as a part of an effort to upgrade the biofidelity and measurement capabilities of current generation frontal crash test dummies. The abdomen was designed to mimic the dynamic stiffness of the human abdomen under steering wheel, belt and airbag impacts in an automotive environment. Instrumentation capable of measuring the deformation of the dummy abdomen was also designed and integrated into the abdomen. This presentation will discuss the features of an abdomen and instrumentation system. In addition, tests conducted to evaluate the performance of the system will be described. Results of these tests will be presented. A number of design changes were instituted based on the results from static and dynamic tests. These design changes will be described.

INTRODUCTION

Recently, Rouhana [1989] described the design of an abdominal injury assessment device. This frangible abdominal insert was fabricated from a styrofoam block and was designed to fit the Hybrid III and TAD-50M dummies. It was used to quantify the effects of belt loading on the lower abdomen. This design exhibited a more "human like" force-deflection characteristic when loaded by belts, and was capable of measuring the maximum abdominal deformation. The abdominal insert is frangible and has to be replaced after each test. The insert was not designed to assess injury potential due to the abdomen being loaded by steering wheels and airbags.

Prior to the development of the frangible insert, attempts have been made to design non-frangible, biofidelic abdominal inserts. Mooney and Collins [1986] reported on the development of a foam loaded airbag insert developed for the Hybrid III dummy. This device was designed to assess injury potential due to steering wheel loading, and to relate abdominal compression to the pressure generated in the airbag. Its pressure-deflection response was dependent on shape of the impactor and the location of impact.

More recently, Ishiyama et al. [1994] have reported on the design of an abdominal insert made of Neoprene - 15. These authors also designed and tested a strain gauge based device to measure time-wise compression of the abdomen as it was loaded by a rod shaped impactor. This device was also designed to assess injury potential due to steering wheel. The time-wise deflection of the abdomen was measured by the strain gauge device in the mid-sagittal plane of the abdomen. The authors reported that their device could not be reused when the steel band housing the strain gauges was deformed plastically. Redesign was needed to solve the problem of bending fracture of the steel band. They also pointed out the need to obtain test data to better characterize the impact response of the human abdomen.

As a part of the current dummy design effort funded by the NHTSA, GESAC staff in consultation with NHTSA staff decided to refine the design of dummy abdomen. The goal of the effort was to design a biofidelic, non-frangible device capable of providing time-wise deformation and velocity of deformation data as the abdomen was loaded by belts, steering wheels, and airbags.

DESIGN OF THE ABDOMEN

As a part of the design procedure, a survey of prior literature was conducted to identify the response characteristics of the abdomen when loaded by steering wheels, belts and airbags at various velocities. The results of this survey are discussed in detail in Rangarajan, et al. [1995] and will be summarized below.

Response of Abdomen to Belt Impacts

Miller [1989] conducted belt loading experiments on anaesthetized pigs to develop response corridors for belt impacts. In addition, Rouhana, et al. [1989] conducted belt loading experiments on porcine cadavers. These data were then self normalized (normalized to account for variation in zoomorphy of test subjects) by Rouhana et al., scaled to human scale and reported by them. The authors report that at the 0.05 level of significance, there were no differences between:

1. Mean porcine cadaver stiffness and mean live anaesthetized porcine stiffness.
2. Mean porcine cadaver stiffness and mean human cadaver stiffness.
3. Mean scaled porcine cadaver stiffness and mean human cadaver stiffness.

However, porcine cadaver data were obtained using standard safety belt material while human cadaver data were obtained using a rigid bar as the loading surface. In addition, impact velocities in the human cadaver study were higher than those in the porcine study. Bearing in mind that there was a paucity of data to define belt loading behavior of human cadavers, the authors defined target stiffness of the abdomen to be 23.0 N/mm.

Response of the abdomen to rod impacts

Cadaver impact tests conducted by Cavanaugh [1986] and Nusholtz [1986] were analyzed in order to obtain response characteristics of the abdomen when impacted by rods and steering wheels.

Cavanaugh conducted impact tests on seated cadavers. A one inch diameter horizontal bar was used to load the abdomen at about the L3 level. Tests were conducted at several impact velocities with impactors with two different masses. Cavanaugh segregated the response of the abdomen into two groups based on impact velocity. Impact velocities in the low speed tests varied from 4.87 m/s to 7.24 m/s with an average of 6.1 m/s. It is possible that in tests conducted by Cavanaugh, the impacting rod engaged only the soft part of the abdomen and the involvement of the rib cage in generating the response was minimal. Therefore, a response corridor for the soft abdomen was obtained from the low speed impact tests conducted by Cavanaugh. This is shown in Fig. 1.

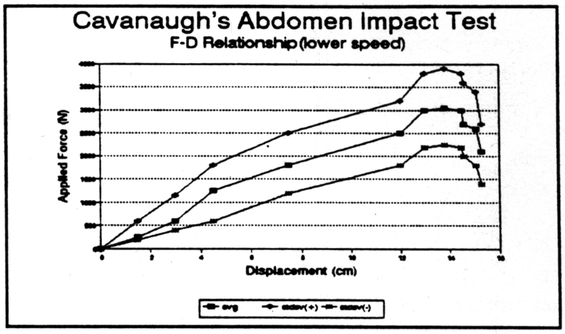

Figure 1. Mean response and corridors for Cavanaugh's low-speed tests.

The average stiffness as seen from Fig.1 is approximately 21 kN/m. This is quite similar to the stiffness of 23 kN/m reported by Rouhana, et al. from their analysis of porcine cadaver and anesthetized porcine data.

Response of the abdomen to steering wheel impacts

Nusholtz et al. [1985] conducted frontal impact tests using unembalmed, re-pressurized human cadavers. Steering wheels were mounted on an impactor weighing 25 lbs and they impacted cadavers seated on tables around the L3 level. The average stiffness was calculated to be approximately 55 kN/m. The average stiffness during the first 4 cm penetration was about 45 kN/m while the stiffness for penetrations greater than 4 cm was about 70 kN/m. This increase in stiffness for higher penetrations probably arises from engagement of steering wheel rim with lower rib structure. Therefore, a response corridor for the abdomen including its interaction with the rib cage was developed from Nusholtz's data which is shown in Fig. 2.

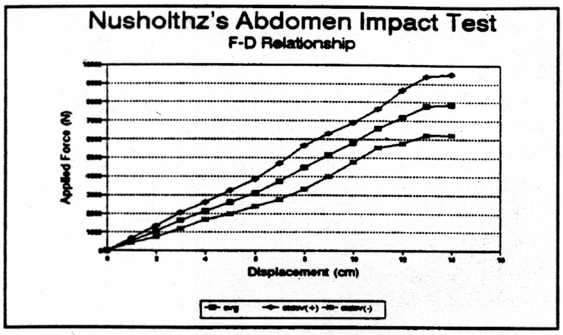

Figure 2. Mean response and corridors for Nusholtz's tests.

Prior to embarking on the design effort a set of design criteria were developed to guide design efforts. These criteria are similar to those proposed by Rouhana et al. [1989] to guide the development of the frangible abdomen. They are as follows:

1. The density of the response element should be such that human like mass and mass distribution are achieved in the design.
2. The design should incorporate elements to measure loads from deploying airbags on the abdomen in addition to belt and steering wheel loads.
3. The force-deflection characteristics of the abdomen must fall into established corridors.
4. The structural integrity of the abdomen must be maintained under loading that can be generated during submarining.
5. Restitution properties of the abdomen should be well tabulated. It should be matched with the restitution properties of the dummy thorax.
6. Batches of material used to design the abdomen should exhibit minimum variability in material properties. The material should be easily machinable or moldable.
7. The abdomen should not generate response when the dummy bends under impact loads. Response should be generated only when the response element is loaded directly.
8. The design should incorporate elements to give indications when the lap belts leave the Anterior Superior Iliac Spine (ASIS).
9. Initially, the abdomen should be designed to fit into the prototype TAD-50M pelvis. This abdomen will be redesigned to fit the final design of the pelvis.
10. The new pelvis-abdomen design should exhibit biofidelic behavior when submarining.

Design of the two-segment abdomen

The rod shaped horizontal impactor used by Cavanaugh probably loaded the soft part of the abdomen near the pelvic cavity. Therefore, it seems reasonable to assume that the response corridors shown in Fig. 1 represents response of the soft abdominal tissue. However, the wheel shaped impactor used by Nusholtz, most probably engaged the ribs as it penetrated the soft part of the abdomen. Thus, it seems reasonable to assume that the corridor shown in Fig. 2 represents the response of a combination of the softer parts of the abdomen and rib cage. This being the case, it was decided that the abdomen should be designed as two separate, upper and lower segments. Figure 3 shows the two abdominal segments integrated with the TAD-50M dummy.

The lower segment closer to the pelvic cavity would respond in a way similar to the response of the soft abdominal tissue. The response of this segment would be defined by the corridor shown in Fig. 1. This corridor will adequately represent the force-deflection response of the lower abdomen at loading rates up to about 7 m/s.

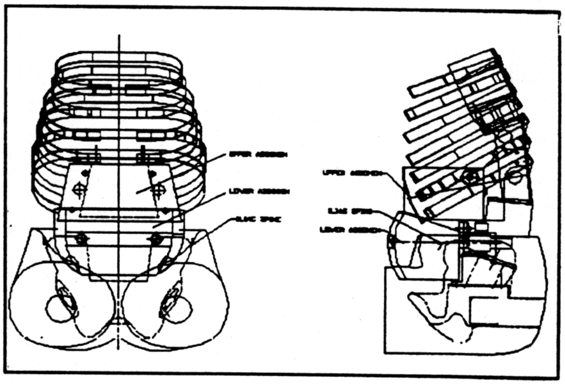

Figure 3. Front and side views showing two abdominal segments integrated in the dummy (TAD-50M).

The upper abdominal segment was attached to the rib cage and its response was influenced by the response of the rib cage. Therefore, the response corridor shown in Fig. 2 would define the response of the upper abdomen. It is believed that the response corridor shown will adequately represent the force-deflection response of the abdomen/rib cage system in the velocity range of 4 to 13 m/s.

Preliminary design of lower abdominal bag - The lower segment was made of two layers of foam inside a stiff kevlar bag. The foams are commercially available and were chosen using lumped mass modelling techniques and static testing so that the combination provided the desired stiffness. Figures 4 through 6 show the plan, side and frontal views of the lower bag. These figures illustrate the salient features of the design.

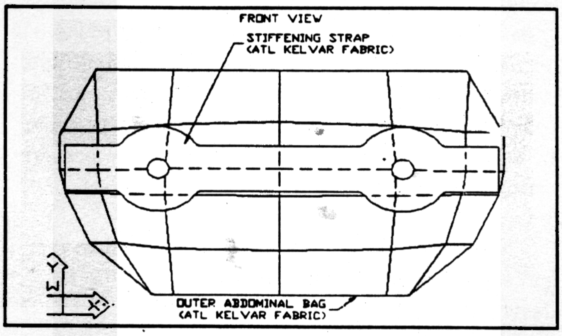

Figure 4. Front view of lower abdomen showing stiffener.

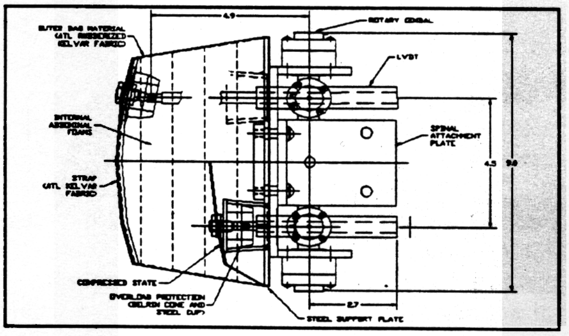

Figure 5. Plan view of lower abdomen.

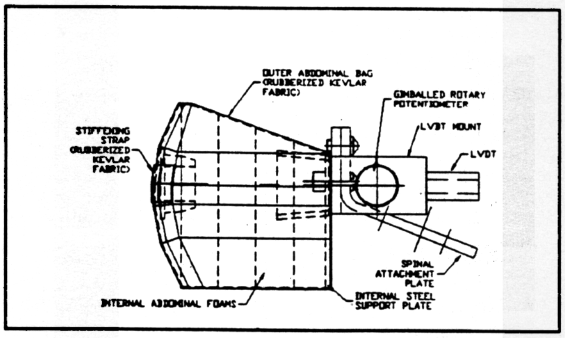

Figure 6. Side view of lower abdomen.

The lower abdomen had a 2" thick base layer foam of L-200 Minicel. A front layer of 3" thickness of the 6# Polyester Urethane was added to the base layer and cut as needed to conform to the desired contour. The foam layers were not glued together. The foam assembly was sealed in a kevlar bag. The lower abdomen incorporated a zipper in the cover material to allow access to the foam and instrumentation inside. The zipper was located in such a way that it crossed the entire bottom side of the lower abdomen bladder and extended approximately 2.5" up each side. The zipper was centered across the lower side of the abdomen so that it extended evenly up each side. The zipper was located with its centerline at a distance of 0.75" from the back edge of the rear support.

A strong glue was used to bond the zipper edges to the abdominal bladder material. The fabric was then sewn together with Kevlar thread. A layer of bladder or gasket material was sewn onto the inside of the upper abdomen bag along one track of the zipper. This acted as a gasket to minimize air leakage through the zipper in the upper abdomen.

The lower abdomen bag was attached to the dummy around the lumbar spine region and sat in the pelvic cavity. The lower bag was instrumented with two linear potentiometers which were attached to the front of the bag. The back of each potentiometer was attached to a double gimbal system. The double gimbal system was instrumented with two rotary potentiometers. Thus, 3-D displacement of the points at which the linear potentiometer is attached to the bag front can be measured as a function of time. The total weight of the abdomen together with the instrumentation system was 2.6 kg.

Design of the upper abdominal bag - Figures 7 through 9 show the plan, side and rear views, respectively of the upper abdomen and illustrate important design features. The abdominal bag was constructed out of Kevlar fabric. Foamex polyurethane open cell foam was used to fill the bag.

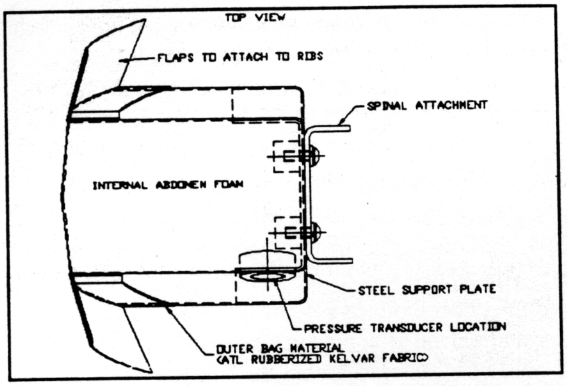

Figure 7. Plan view of the upper abdomen.

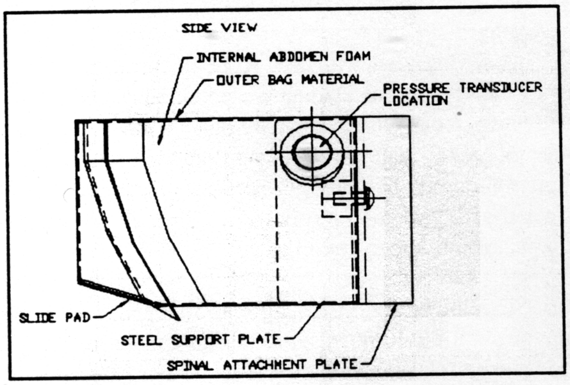

Figure 8. Side view of the upper abdomen.

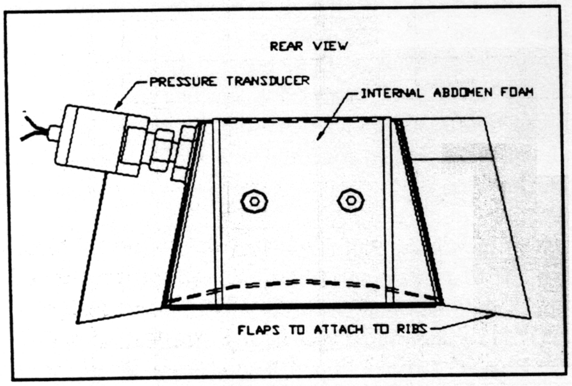

Figure 9. Rear view of upper abdomen.

The abdomen assemblies required a foam thickness of slightly greater than 5" and the foam was only available in 4" thickness. So, the foam was layered in two pieces. The upper abdomen included a constant thickness back piece of 1.5" to 2", which rests flush against the internal bracket. A second piece of foam was then shaped to fill the remaining area. In addition, the back piece of foam was cut 0.25" oversize so that the pieces would compress together slightly upon assembly and hold themselves in place.

Like the lower abdomen assembly, the upper abdomen design also incorporated a zipper for ease of access to the foam and instrumentation. Details of the procedure used to attach the zipper to the bag were similar to those used to attach the zippers to the lower abdomen and have been discussed above. The important difference between the lower and upper abdomen design was that the upper abdominal segment was designed to perform like a sealed, foam loaded airbag and thus efforts were made to ensure that the bag did not leak air. The upper segment instrumented with a pressure transducer was attached to the lower ribs in the front and the lower thoracic spine in the rear. The weight of the upper abdomen together with the pressure transducer was 1.2 kg.

Since the upper abdomen was attached to the ribs and was expected to move with the ribs, the aim was to record pressure in the bag and also the compression of the ribs using the lower DGSPs during tests. The Double Gimballed String Potentiometers (DGSP) were a part of the TAD-50M design.

Test and Evaluation of the Preliminary Design

Static Testing - Both upper and lower abdomens were assembled into the dummy and tested under quasi-static conditions on an Instron machine. Static testing was conducted to ensure proper functioning of the newly designed components. The assemblies were also loaded with various shaped load application heads to examine the effect of their shape on the performance of the abdominal system. Table 1 provides information about the load application heads used in static testing.

Table 1. Shape of Application Heads Used in Static Testing

Indentor Number	Size	Indentor Shape
1A	2" Diameter	Circular Indentor
1B	2" x 6"	Side of Cylinder
2	2" x 6"	Rectangular Indentor
3	1" x 14"	Bar Loading

The test articles were loaded to their maximum compression to evaluate the performance of the overload stops and the instrumentation. Tests were also repeated to assess durability and repeatability of the design. The stroke of the Instron machine was compared with the compression recorded by the linear potentiometers in the lower abdomen. No problems were noticed during static testing. A series of dynamic tests were then conducted on the test articles. These tests are described below.

In an effort to confirm that the design did not cause spurious chest compression under bending loads, the dummy was seated in a chair and a load applied in the posterior-anterior direction. The signals from the thoracic DGSPs were monitored. Under static conditions, minimal chest compression in response to spinal bending was noted.

Dynamic Testing - Dynamic testing was performed on both the upper and lower abdomen assemblies using a linear impactor. In preparation for the impact, the dummy was seated on a table with the legs extended straight in front and its back unsupported. The arms of the dummy were placed in the raised position. The dummy was positioned at right angles to the impactor head and an upright posture was maintained throughout the testing.

The impactor head was attached to a load cell and accelerometer was attached to the load cell. Another accelerometer was attached to the spine of the dummy on the same plane as the impactor. High speed film and video were used to film the test sequence.

Three different types of impact tests were conducted. In the steering wheel tests, the upper abdomen was loaded by an impactor shaped like the lower half of a steering wheel. The impactor was constructed from tubular steel and had a diameter of approximately 2.54 cm (1"). The wheel was inclined at an angle of 45 degrees. The mass of the impactor was approximately 32 kg. This impactor was similar to the one used by Nusholtz. The location of impact was centered on the upper abdomen. Tests were conducted at 4, 6.5, and 10.8 m/s.

The lower abdomen was loaded using a solid Aluminum rod 30 cm long with a diameter of 2.54 cm. The mass of the impactor was 32 kg. This impactor was similar to the one used by Cavanaugh. The location of impact was approximately at L3 and was centered on the Linear potentiometers of the lower abdomen. Tests were conducted at 4.9, 6, and 7.2 m/s.

The lower abdomen was also loaded with a belt stretched between the arms of a yoke. The seat belt was pre-tensioned slightly to minimize slack in the belt. The mass of the impactor was 32 kg. The location of impact was centered on the linear potentiometers of the lower abdomen. Tests were conducted at 1, 3, and 6 m/s.

A list of all dynamic tests is provided in Table 2.

Table 2. Dynamic Test Conditions

Test Number	Impactor	Target (U / L)	Velocity (m/s)	Film (Y/N)	VCR (Y/N)
5B	SW	U2	6.5	Y	Y
6A	SW	U2	6.5	Y	Y
7A	SW	U2	8.8	Y	Y
7B	SW	U2	9.4	Y	Y
7C	SW	U2	10	N	Y
7D	SW	U2	12.1	Y	Y
8A *1	SW	U2	6.7	Y	N
8B	SW	U2	3.9	N	N
18A	SW	U1	4.0	Y	N
19A	SW	U1	6.5	Y	N
20A	SW	U1	10	Y	N
2A	Rod	L2	4.9	N	Y
3A	Rod	L2	6.0	Y	Y
4A	Rod	L2	7.2	Y	Y
4B	Rod	L2	7.2	Y	Y
9A	Rod	L2	4.0	N	Y
14A	Rod	L1	4.9	Y	N
15A	Rod	L1	4.0	Y	N
16A	Rod	L1	6.0	Y	N
17A	Rod	L1	7.2	Y	Y
10B *2	Belt	L2	3.0–	N	N
11A	Belt	L2	6.0	Y	Y
12A *3	Belt	L1	3.3	Y	N
12B	Belt	L1	3.3	N	N
13A	Belt	L1	6.0	Y	N

Notes:
U = Upper abdomen ; L = Lower abdomen
*1 This test was a low hit on the upper abdomen assembly to determine possible problems caused by the gaps between the abdomen assemblies.
*2 Belt Load Cell added to instrumentation for this

test. belt tension increased.
*3 Left Abdominal LVDT malfunction.

In addition, sled tests were conducted to evaluate the dynamic response and robustness of the design.

Test Results and Discussion

This series of tests proved the efficacy of the design and testing approach. Results from the test series indicated that the modelling approach was sound and yielded valuable design guidance. Finally, the models could be used to improve the design post-test, and to overcome some of the shortcomings identified during testing.

Figure 10 shows the response of the second version of the lower abdomen to belt impacts at 3 m/s and 6 m/s. During the 3 m/s impacts, the tension in the belt varied from "very snug" to "not snug" in order to identify the effects of belt tension on the test results. Belt tension was not measured in these tests. In general, it is seen that the response of the foams used in this abdomen was stiffer than the target stiffness. Belt stretch was not measured in these tests.

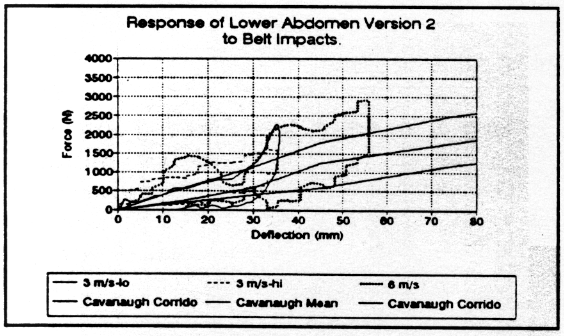

Figure 10. Force-deflection response of lower abdomen to belt impact also showing Cavanaugh low speed corridor.

Figures 11 shows the response of lower abdomen 2 to rod impacts at 4 m/s, 6 m/s and 7.2 m/s while Fig. 12 shows its response to rod impacts at 4.0 m/s and 7.2 m/s respectively. Tests at impact speeds of 4 m/s and 7.2 m/s were repeated after adjusting the linear impactor's stroke to achieve different levels of abdominal compression. Rapid stiffening of the foam in the 4 m/s tests when compression reaches about 60 mm can be attributed to the foam bottoming out.

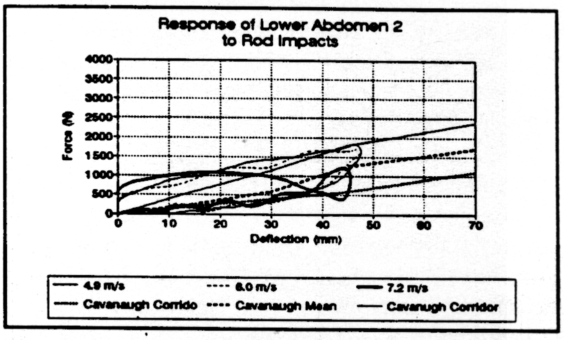

Figure 11. Force-deflection response of abdomen to rod impact also showing Cavanaugh low speed corridor.

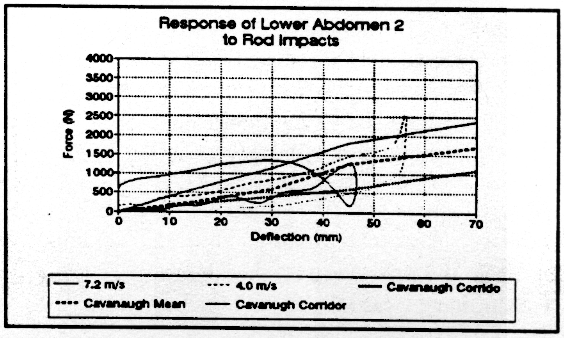

Figure 12. Force-deflection response of abdomen to rod impact also showing Cavanaugh low speed corridor.

The upper abdomen was tested using an impactor shaped like a steering wheel. Pressure-time history from the pressure transducer in the abdomen, force-time history from the impactor load cell and also compression-time history from the left lower DGSP of the TAD-50M were recorded. It is important to point out that the DGSP started responding after the abdomen had been compressed about 25 mm when the lower ribs started moving with the abdomen. It is also important to point out that prior tests conducted on the TAD-50M seemed to suggest that the DGSP could not provide accurate compression information above loading rates of approximately 6-8 m/s.

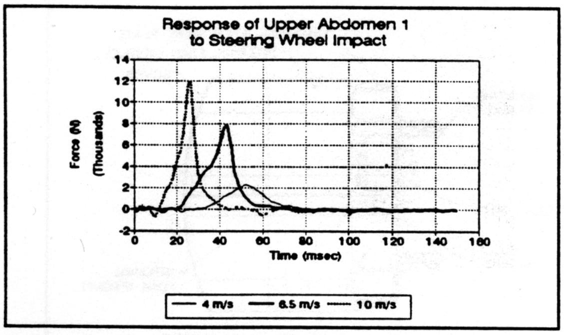

Figure 13. Response of upper abdomen to steering wheel impact force vs time plot.

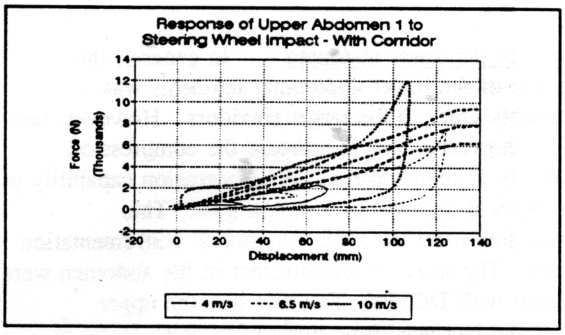

Figure 14. Response of upper abdomen to steering wheel impact with Nuscholtz corridor.

The response of the upper abdomen 1 to steering wheel impact is illustrated in Figs. 13 and 14. These figures show the force - time response of the upper abdomen / lower rib system. The force response of the system was combined with the compression recorded by the left lower DGSP on the TAD-50M to develop the force - deflection response of the system. Figures 12 and 13 also show the Nusholtz corridor which was the performance target for this system. Even though the system appears a bit stiffer than the target, it is to be remembered that the DGSP deflection probably started after the abdomen was compressed about 25 mm. The data plotted in Fig. 13 and 14 were obtained from instantaneous recordings of the DGSP compression and the impactor load cell signals.

Sled tests were also conducted to evaluate the response of the abdominal segments to belt loading on sleds. There was a need to determine if the design would allow the belts to be caught in the crevice between the two abdominal segments during impact tests. Sled tests were conducted at 30 mph. Two tests were conducted with the dummy sitting on a hard seat. In the first test, the dummy was sitting in "normal" seated posture and was restrained by a 3-point belt. In the second tests, the dummy was seated on the same seat but in a slumped posture to promote submarining. Problems with the data acquisition system at the laboratory prevented recording and analysis of dummy response data. Photographic evidence suggests that the dummy behaved normally during impact. However, the lap belt was caught in the crevice between the two abdominal segments when the dummy submarined.

Discussion of Test Results and Design Revisions

A preliminary design of a two-segment dummy abdomen was fabricated and tested. Linear impactor and sled tests were conducted. Rod and steering wheel shaped impactors and a belt stretched between a yoke were used in impact tests. The lower abdomen was instrumented with a linear potentiometer attached to a gimbal system. The upper abdomen was instrumented with pressure transducers.

The design of the abdominal segments was revised based on test results. In this section, test results will be summarized and the revised design will be described.

Design of upper abdomen

Tests of the sealed, foam filled bag used to generate the response of the upper abdomen revealed that its response could vary with impact location. Also, tests revealed that correlating the pressure in the bag with compression would be a difficult task. It was decided not to pursue this concept any further in the near term.

It was also decided to redesign the upper abdomen as a foam filled bag similar in concept to the lower abdomen. However, the foam used to fill the upper abdomen would have to be stiffer than the foam used to fill the lower abdomen in order to meet the Nusholtz corridor. Since the abdomen was not designed as a sealed bag, it was decided that it could be designed as a cordura fabric bag filled with foam. This would make it easier to manufacture the abdomen and also reduce the cost of manufacture.

The design tested had no provision for measuring abdominal compression. It was also decided that in the next design, the upper abdomen would be instrumented with a high-tension string pot and that an accelerometer be attached to the front of the bag. The accelerometer would be attached to pick up the response of the abdomen to airbag slap. As in the preliminary design, the upper abdomen was to be rigidly attached to the lower rib cage so that compression of the upper abdomen could also be tracked by lower rib displacement measurement system. Figures 15 through 17 show the front, side and top views of the current upper abdomen design together with details of the instrumentation system in place currently. This revised design has been integrated into the advanced dummy and tests are in progress to evaluate the performance of the design.

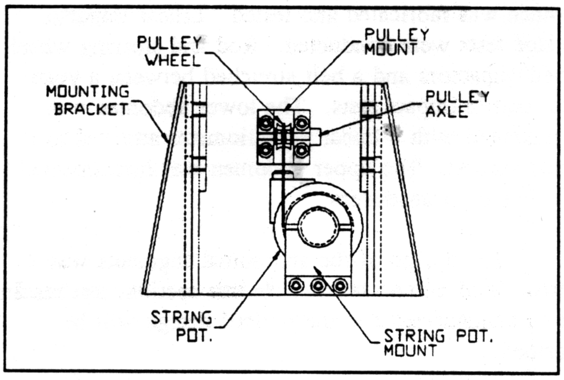

Figure 15. Front view of current upper abdomen.

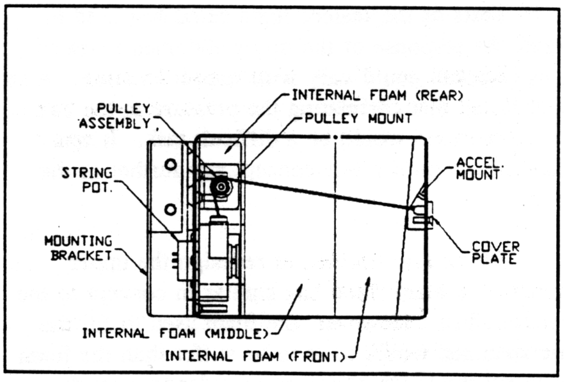

Figure 16. Side view of current upper abdomen.

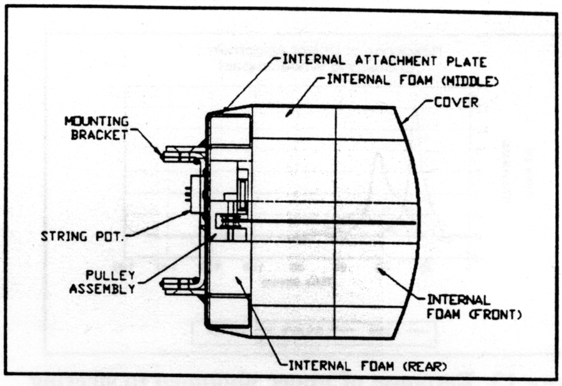

Figure 17. Top view of current upper abdomen.

Design of the lower abdomen - In general, the response of the lower abdominal segments was reasonably close to the target corridors. However, test results showed a need to increase the compression capability of the abdomen. A compression capability of 4 inches was selected as a design goal. This necessitated redesign of the abdominal instrumentation system. The linear potentiometers in the abdomen were replaced with DGSPs. This bag like the upper abdominal bag was to be made of cordura fabric in order to reduce manufacturing time and cost.

Figures 18 and 19 show the top and side view of the current lower abdomen design together with details of the instrumentation system in place currently. The lower abdominal bag has been redesigned, fabricated and integrated into the advanced dummy. A rigorous testing program has been designed to evaluate the performance of this design.

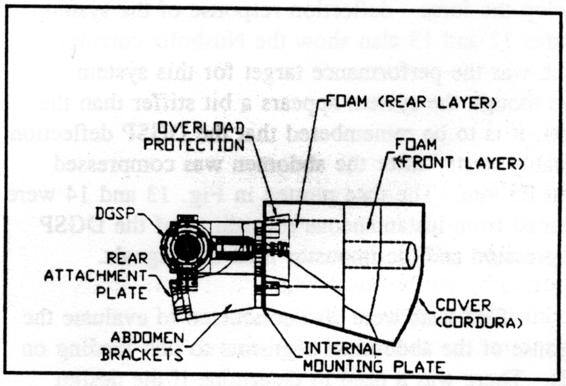

Figure 18. Side view of current lower abdomen.

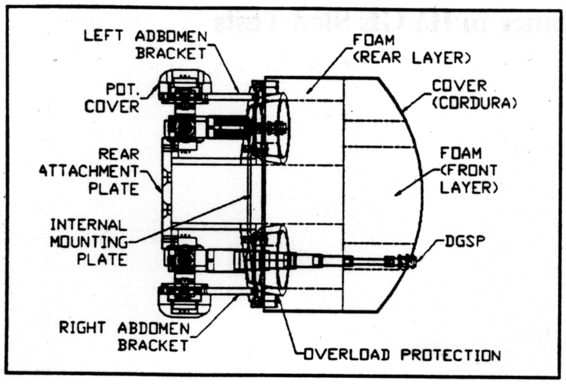

Figure 19. Top view of current lower abdomen.

Design of outer skin - Limited sled tests pointed out the need to shield the gap between the upper and lower abdominal segments from belt intrusion. It was decided to prevent belt intrusion by incorporating two features in the revised design. First, a shaped piece of non-structural foam was inserted into a pouch sewn on top of the lower abdomen bag. Second, an outer skin made of stiff material was designed to cover both abdominal segments. Some details of the shaped foam and the outer skin design are shown in Fig. 20. These concepts will be tested in the near future.

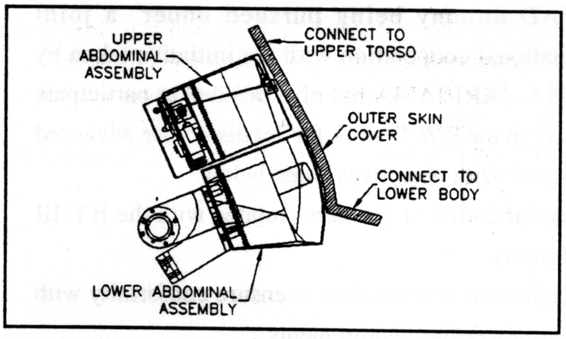

Figure 20. Outer skin covering for abdomen segments.

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