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MILITARY VEHICLE UNDERBODY ARMOR PLATE ATTACHMENT STUDY

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ABSTRACT

In this paper a new bolt attachment method was explored, where the attaching bolts were divided into two sets. The first set of bolts was tightened and was used to connect the underbody plate to the hull under ordinary operations. The second set of bolts connecting the plate and the hull were not tightened and had some extra axial freedom. Under blast loading, the first set of bolts would break due to high tensile and shear loads, but the second set of bolts would survive due to extra axial freedom which allows the plate and the hull vibrate and separate from each other to a certain extent. A simulation model was developed to verify this concept. Three underbody plate-hull connection approaches were simulated and analyzed: 1) all tightened bolts, 2) some bolts not fully seated, 3) all bolts not fully seated. The simulation results show that with option 1), 100% of the bolts broke under the blast loading. With option 2) the not fully seated bolts survived and continued to attach the plate to the hull. And with option 3) all the bolts not fully seated also survived. This new concept might provide an improved approach for attaching the underbody armor plate to the vehicle hull which would enhance the occupant and vehicle survivability while reducing engineering complexity and cost.

1. INTRODUCTION

Military ground vehicles usually require installation of an underbody armor plate to enhance the protection of crew members from land mine blast or improvised explosive device (IED) threat. In most cases the underbody plate is attached to vehicle hull by tightened bolts. Previous experience and numerical simulation results indicated that to withstand the extremely high underbody blast loading, a large number of bolts would be required to connect the underbody plate to the vehicle hull. In line with conventional thinking, a substantial compressive force is created along the underbody plate/hull interface from the blast effect. However, a significant vibration wave is generated along the interface in some cases causing extreme, localized, tensile and shear loads which act on individual or small subsets of fasteners. The need for a large quantity of bolts to attach the underbody plate makes the engineering design, manufacturing and maintenance difficult and costly.

In this study, a new bolt attachment method was explored, where the attaching bolts were divided into two sets. The first set of bolts was tightened and was used to connect the underbody plate to the hull under ordinary operations. The second set of bolts connecting the plate and the hull were not fully seated. That is, they were not tightened and had some extra axial freedom. Under blast loading, the first set of bolts would break due to high tensile and shear loads, but the second set of bolts would survive due to extra axial freedom which allows the plate and the hull to vibrate and separate from each other to a certain extent. The following sections describe the simulation model development and discuss the results obtained.

2. BOLTS AND SIMULATION MODEL SETUP

The bolts used in this study were Grade 8 with diameter 5/8” or 3/4". The ultimate tensile strength (UTS) is 150,800 N for the 5/8” bolts and 222,860 N for 3/4” bolts, respectively, as specified in SAE J429 [1].

The underbody armor plate attachment study was carried out by using computer modeling and simulation. Numerical simulation software LS-Dyna was utilized to model the vehicle hull floor, underbody armor plate and bolt attachment, all assembled with a full vehicle structure. For simplicity the bolts were modeled with beam elements with specified diameters and clamping lengths. A stress-strain curve, as shown in Figure 1, was used to describe the elastic-plastic bolt material property. Neither ATD models nor occupant injury numbers were involved in this study. However, ATD's could be added to the model with no adverse effects on the UB plate attachment method or integration to the vehicle hull which would impact the results of this study.

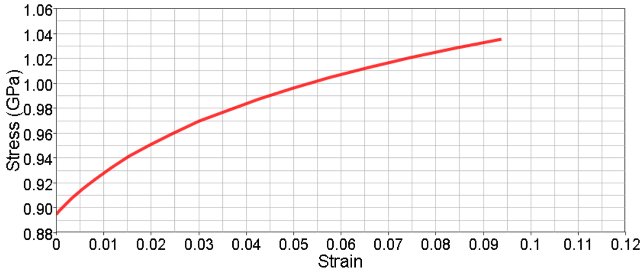

Figure 1 Stress-Strain curve for Grade 8 bolt material

A bolt failure was considered in this study by defining a failure index,

$$Failure\ Index = {}^{N_{rr}}/_{N_{rr,UTS}} \tag{1}$$

Where N_{rr} is the bolt tensile load and $N_{rr,UTS}$ is the ultimate tensile strength. When the Failure Index was greater than unit, the bolt was considered failed and removed from the simulation. No shear or bending failures were considered in this study due to lack of data.

3. PLATE ATTACHMENT STUDY

A generic military vehicle bottom hull and a solid underbody armor plate with V-shaped bottom, as shown in Fig. 2, were employed to carry out this study. The thickness at the V-bottom plate center is 2.5", and on the edge it is 0.5". The weight of the V-bottom plate is about 4060 lbm.

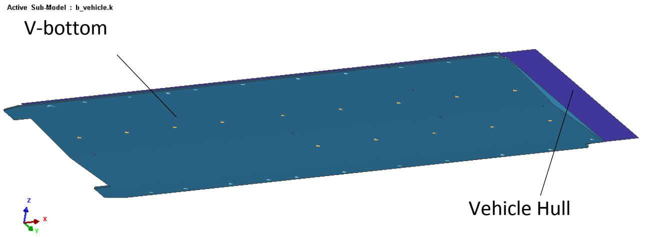

Figure 2 Vehicle bottom hull and underbody armor plate with V-shaped bottom (left-rear-bottom view)

3.1 Case 1 - All Bolts Fully Seated

In the first case of the study, all bolts attaching the V-bottom plate to the vehicle hull were fully seated or tightened. A typical bolt connection is depicted in Fig.3. Note that this drawing is not to scale and a connection insert at the top is not shown. Overall 50 Grade 8 bolts were used to attach the V-bottom plate to the vehicle hulls, where 22 were on the V-bottom perimeter with 5/8" diameter and 5/8" clamping length, 14 on the outer center with 3/4" diameter and 3/4" clamping length, and 14 on the inner center with 3/4" diameter and 1-5/8" clamping length. The bolt distribution and locations are illustrated in Fig. 4, where some bolt IDs are given for the following plot reference. For convenience of discussion, the bolts on perimeter were divided into two groups, Group 1 with blue color and Group 2 with red color, as shown in Fig. 4.

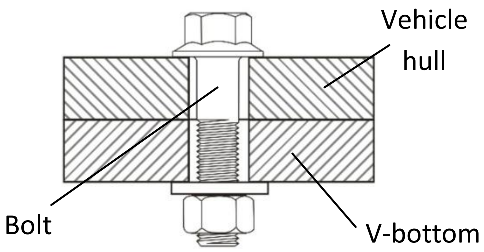

Figure 3 A typical bolt connecting vehicle hull and underbody plate

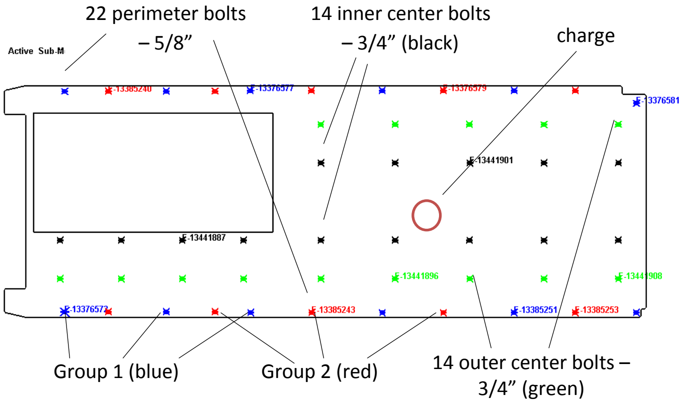

Figure 4 Bolt distribution and locations on the V-bottom plate together with bolt IDs and charge location (top view)

The generic vehicle hull and V-bottom plate together with a full vehicle structure were simulated with an underbody blast load generated by a specified charge located at the crew area center. All the bolts were preloaded to a specified level of the yield strength of the Grade 8 material during the first 5 ms of the simulation, and the charge was then initiated. The deformed hull and V-bottom plate at 7 ms is shown in Fig. 5. Time histories of some representative bolt axial force and failure index are given in Figs. 6-11.

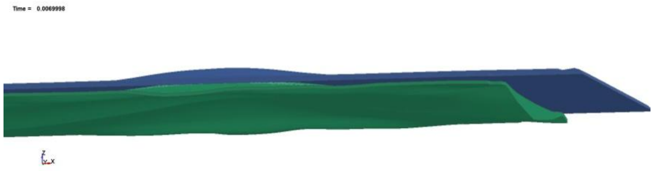

Figure 5 Hull and V-bottom plate deformation at 7 ms (left-bottom view)

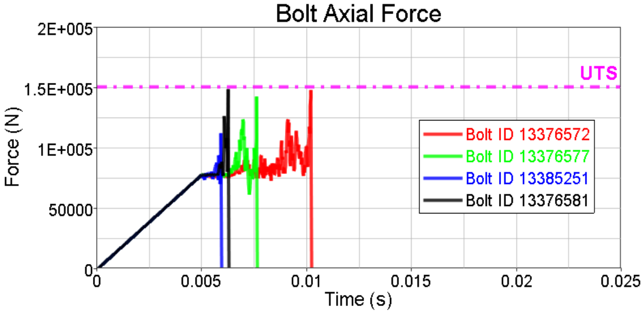

Figure 6 Time history of perimeter bolt Group 1 axial force – Case 1

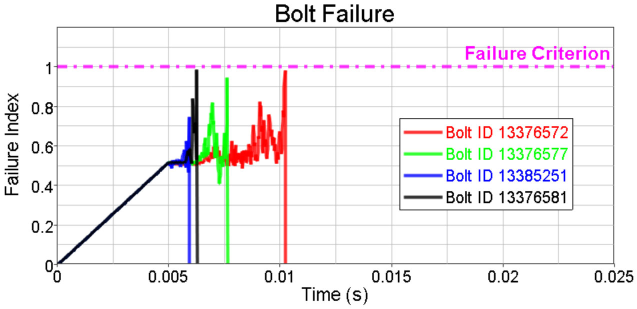

Figure 7 Time history of perimeter bolt Group 1 failure index – Case 1

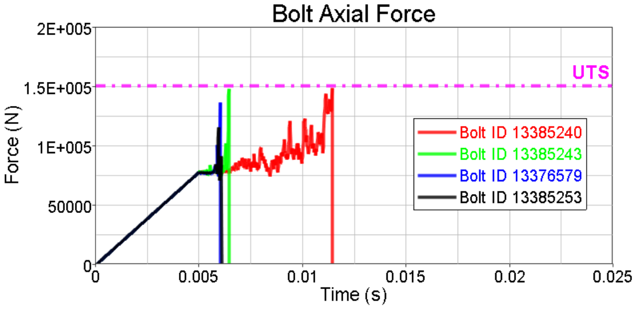

Figure 8 Time history of perimeter bolt Group 2 axial force – Case 1

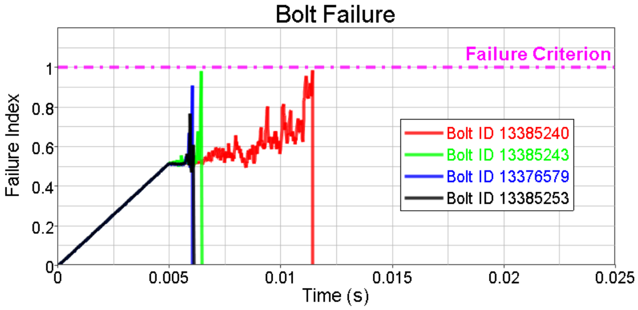

Figure 9 Time history of perimeter bolt Group 2 failure index – Case 1

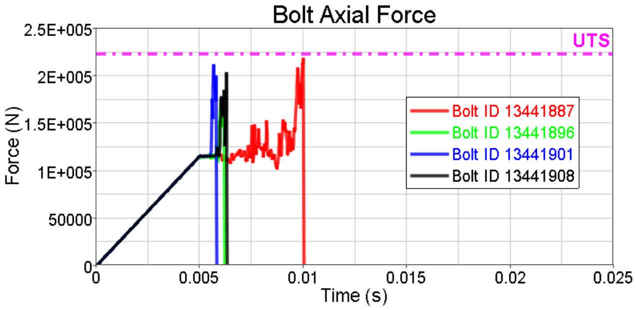

Figure 10 Time history of center bolt axial force – Case 1

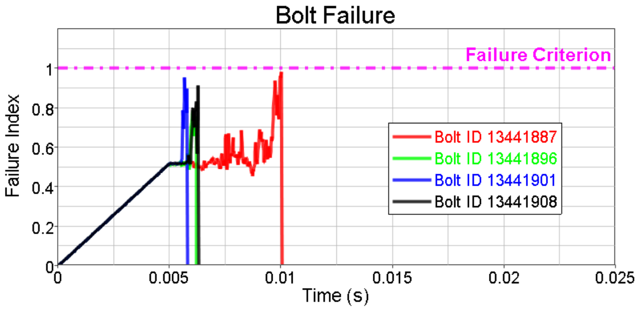

Figure 11 Time history of center bolt failure index – Case 1

From computer animation it could be observed that under the underbody blast loading significant out-phased vibration waves were generated on the vehicle hull and V-bottom plate. This would generate huge and localized tensile loads on individual or small subsets of bolts, and potentially make them fail. For Group 1 bolts on the perimeter, the axial force of Bolt 13385251 quickly increased to the material UTS, and its failure index reached 1 and failed at 5.9 ms after the charge was initiated at 5 ms. Same thing happened to Bolt 13376581 at 6.3 ms, Bolt 13376577 at 7.6 ms and Bolt 13376572 at 10.2 ms, respectively, as shown in Figs 6 and 7. The bolt failure time correlates to their distance from the charge, as could be figured out using Fig. 4. For bolts of

Group 2 on the perimeter and on both outer and inner centers, similar results were obtained, as presented in Figs. 8-11. The simulation results indicated that all bolts were broken if they were initially fully seated or tightened. Thus, the underbelly plate would become detached from the vehicle hull very early in the event.

3.2 Case 2 - A Subset of Bolts Not Fully Seated

From the results of the first case in this study, it was believed that the bolts failed because with fully tightened bolts there was not enough space left for the out-phased hull and V-bottom plate vibration. Thus a concept was developed that if extra axial freedom or space is given to some bolts, these bolts might be able to survive the blast loading.

In the second case of this study, the bolt size, material, number, their locations, preload condition, and charge data were identical to those in the first case. However, instead of fully seated for all the bolts, only the bolts on centers and of Group 1 (blue on Fig. 4) on perimeter were fully tightened. Longer bolts but with same diameters were used for the 10 bolts of Group 2 (red on Fig. 4) on perimeter. They were not fully tightened and a pre-compressed spring was attached to each of them. The spring constant was 450 KN/m and the spring force was 9 KN from a 20 mm initial pre-compression and 18 KN at the maximum compression for each of the springs, both of them much less than the bolt's UTS of 150.8 KN. A Group 2 bolt with spring is sketched in Fig. 12. Again this drawing is not to scale and a connection insert at the top is not shown.

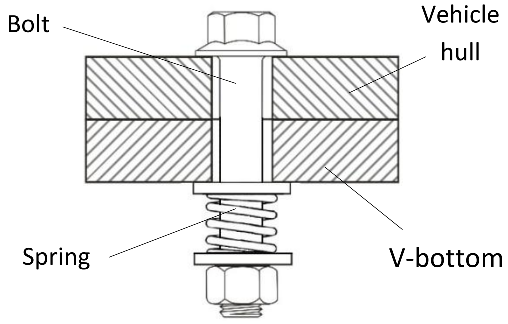

Figure 12 A bolt with spring to connect vehicle hull and underbody plate

This design idea was that the fully seated or tightened bolts would be used to connect the underbody plate to the vehicle hull under ordinary operations. Under blast loading, the fully tightened bolts might break due to high tensile loads, but the longer bolts with dampening springs might survive due to extra axial freedom which allows the plate and the hull to vibrate and separate from each other to a certain extent. After the blast loading, the 10 spring forces together would be strong enough to support the V-bottom plate's weight and retain it to the vehicle hull.

For the simulation of Case 2 the deformed hull and V-bottom together with some bolts and their springs at 7 ms is shown in Fig. 13. Time histories of representative bolt axial force, failure index, spring length and force are given in Figs. 14-21.

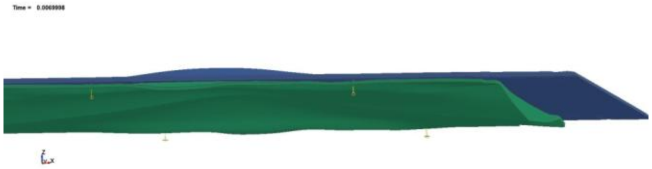

Figure 13 Hull and V-bottom deformation with bolts and their springs at 7 ms (left-bottom view)

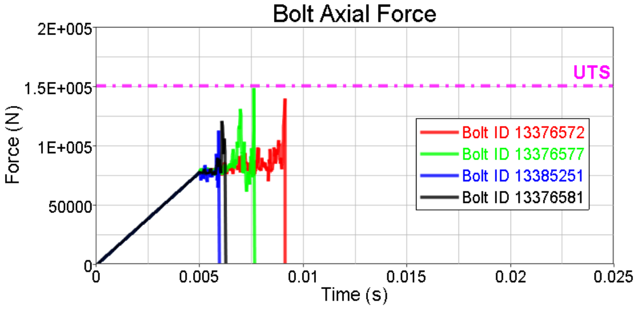

Figure 14 Time history of perimeter bolt Group 1 (tightened) axial force – Case 2

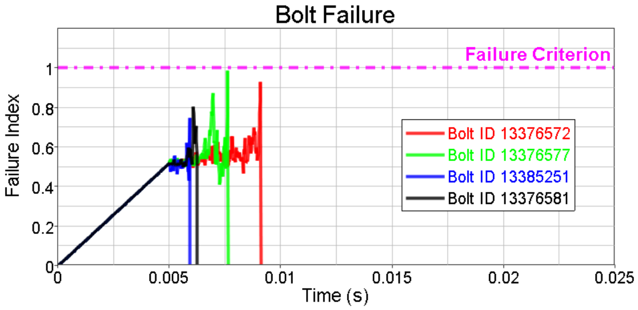

Figure 15 Time history of perimeter bolt Group 1 (tightened) failure index – Case 2

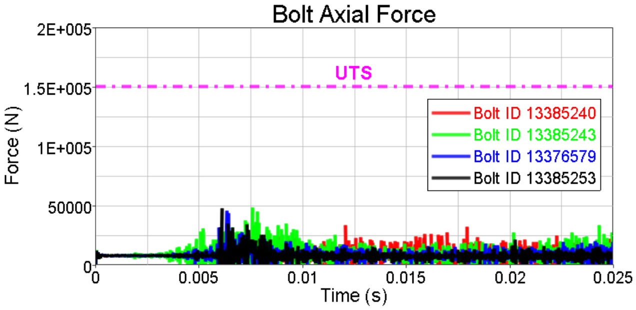

Figure 16 Time history of perimeter bolt Group 2 (longer w/ spring) axial force – Case 2

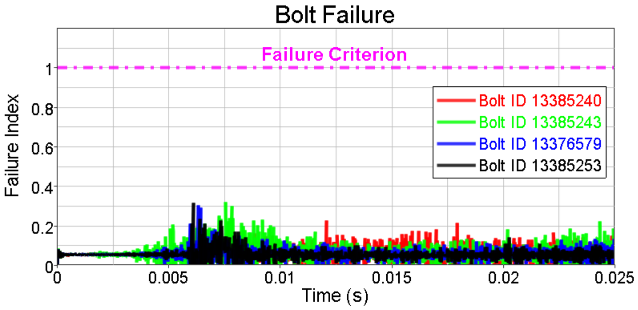

Figure 17 Time history of perimeter bolt Group 2 (longer w/ spring) failure index – Case 2

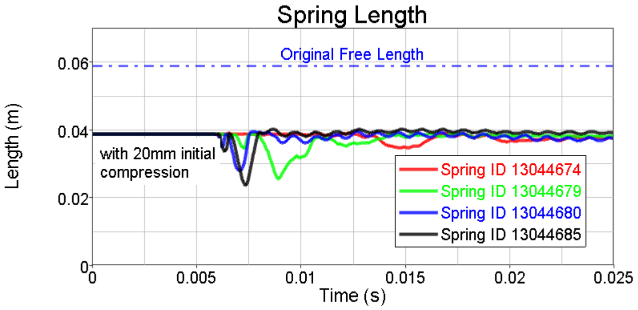

Figure 18 Time history of spring length associated with perimeter bolt Group 2 (longer w/ spring) – Case 2

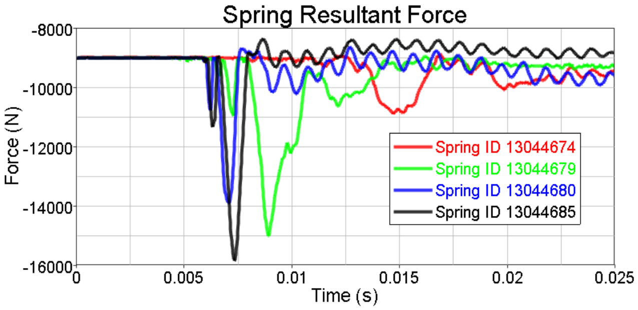

Figure 19 Time history of spring force associated with perimeter bolt Group 2 (longer w/ spring) – Case 2

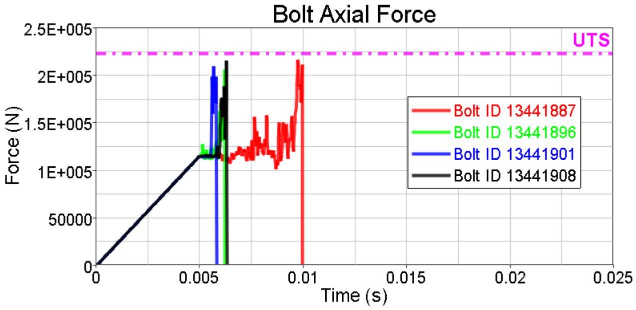

Figure 20 Time history of center bolt (tightened) axial force – Case 2

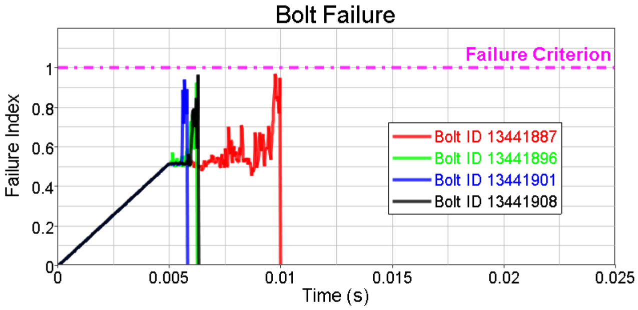

Figure 21 Time history of center bolt (tightened) failure index – Case 2

It could be observed from Figs. 14, 15, 20 and 21 that for those fully seated or tightened bolts in the center or Group 1 on the perimeter, they behaved similarly as before and all bolts failed. However, for those bolts of Group 2 on the perimeter which had longer length with springs, they survived. The peak bolt axial force was only about 1/3 of the material UTS and the corresponding failure index was just about 0.3, as shown in Figs. 16 and 17, respectively. The corresponding spring was further compressed by 15 mm and peak force was less than 16 KN, as given in Figs. 18 and 19, respectively. For spring IDs, please refer to Fig. 22.

3.3 Case 3 – Using Not Fully Seated Bolts Only

Encouraged from the results of Case 2 in this study, the concept of giving bolts extra axial freedom was further explored in Case 3, where fully seated bolts on centers and of Group 1 (blue on Fig. 4) on perimeter were all removed. Only 10 longer bolts with springs of Group 2 on perimeter were remained to connect the V-bottom plate to the vehicle hull. The bolt distribution and locations along with some bolt and spring IDs are illustrated in Fig. 22. The intention of the Case 3 study was to see if the bolts with extra axial freedom could survive the blast loading by themselves. The bolt design and integration of the V-bottom plate to the vehicle hull did not change.

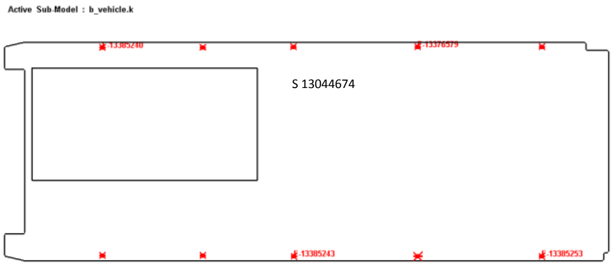

Figure 22 Bolt distribution and locations on the V-bottom plate together with some bolt IDs (in red) and spring IDs (in black) (top view)

Time histories of representative bolt axial force, failure index, spring length and force for the simulation of Case 3 are given in Figs. 23-26.

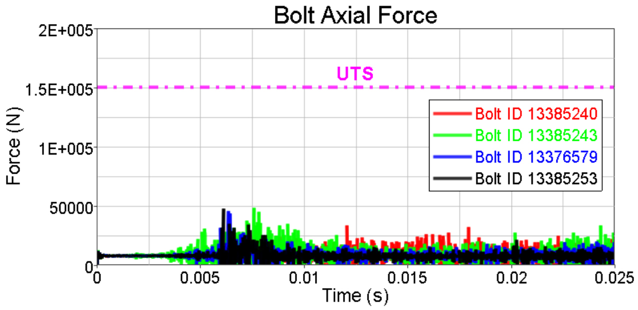

Figure 23 Time history of perimeter bolt Group 2 (longer w/ spring) axial force – Case 3

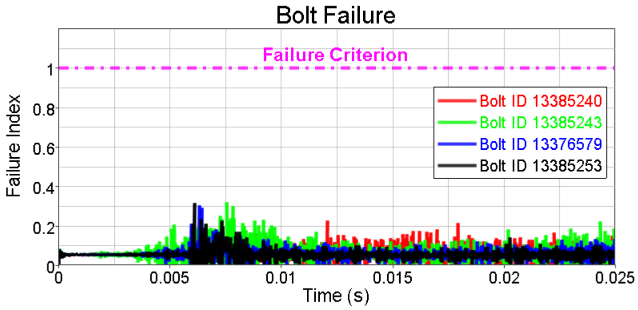

Figure 24 Time history of perimeter bolt Group 2 (longer w/ spring) failure index – Case 3

The simulation results for Case 3 were almost identical to those of the Group 2 bolts with extra axial freedom in Case 2: they all survived the underbody blast loading. As could be observed from Figs. 23-26, the peak bolt axial force was only about 1/3 of the material UTS and the corresponding failure index was just about 0.3. The corresponding spring was compressed by 15 mm more and peak force was less than 16 KN.

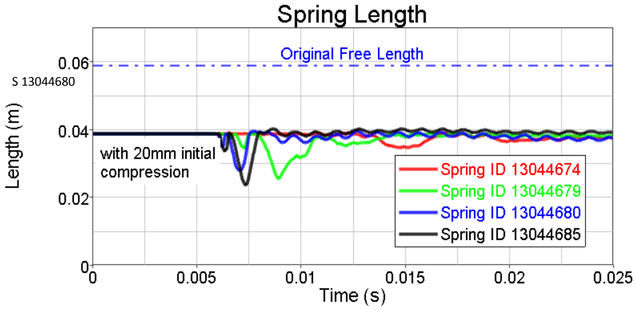

Figure 25 Time history of spring length associated with perimeter bolt Group 2 (longer w/ spring) – Case 3

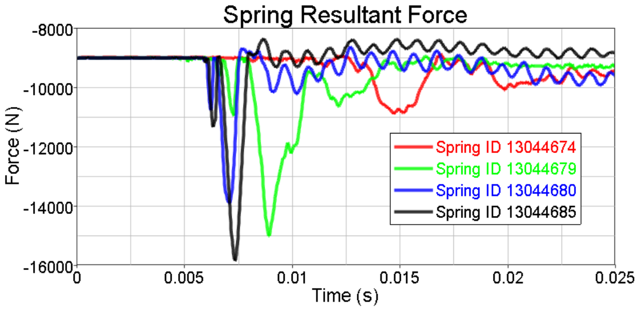

Figure 26 Time history of spring force associated with perimeter bolt Group 2 (longer w/ spring) – Case 3

4. SUMMARY AND CONCLUSIONS

With underbody blast loading, a significant out-phased vibration waves could be generated on the vehicle hull and the underbody armor plate. In some cases, this would result in extreme and localized tensile loads acting on individual or small subsets of bolts, causing potential bolt failure.

Numerical modeling and simulation were used in this study to investigate the bolt attachment methods. The simulation results indicated that in the first case of this study with all bolts fully seated or tightened, 100% of the bolts failed under the blast loading. In the second case of the study, the attaching bolts were divided into two sets. The first set of bolts was tightened to attach the underbody plate to the hull under ordinary operations. The second set of bolts, longer in length and with springs, was not fully seated. That is, they were not tightened all the way which allowed some axial freedom. Under blast loading, the first set of bolts broke due to high tensile loads, but the second set of bolts survived due to this extra axial freedom which allowed the plate and the hull to vibrate independently and separate from each other to a certain extent. The attachment method was further explored in the third case of the study which used 10 partially seated bolts only. The results showed that they survived the blast loading and the V-bottom plate was retained to the vehicle hull.

Two key conclusions could be drawn from this study:
- Fully seated or tightened bolts might be vulnerable under blast loading
- Not fully seated bolts which allow some extra axial freedom potentially have better survivability

This new bolt attachment concept might provide an improved design for connecting the underbody armor plate to the vehicle hull which would enhance the occupant and vehicle survivability while reducing engineering complexity and cost.

Further improvement on the numerical models is recommended to include shear force and bending moment failure modes and use 3D solid elements to model the bolts. Live fire tests are also required to validate and verify the new bolt attachment concept.

Acknowledgement

The authors would like to thank Mr. Jonathan Polom of the TARDEC CSI team for providing some CAD design and bolt information.

REFERENCES

[1] SAE J429, “Mechanical and Material Requirements for Externally Threaded Fasteners”, Revised, September, 2011.