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Demonstration of Impact Performance of the Nuclear Transport Package in On-Site Hypothetical Collision Scenarios by a Heavy Goods Vehicle

Chi-Fung Tso, Arup, UK
Conrad Izatt, Arup, UK

1. Introduction

Spent fuel modules are contained in Module Removal Container (MRC) during on-site transport at the D154 facilities in the Devonport Naval Dockyard in the United Kingdom. The container is transported on its own on a Low Level Transfer Trolley (LLTT) and accommodated within a Transfer Frame. The LLTT travels on rails and moves either under its own power or towed by a Rail Tug Unit. The Transfer Frame provides a secure means of support to the MRC during transit and provides impact protection in the event of collision.

The MRC is accommodated within the Transfer Frame by way of a sub-frame assembly. It rests on its sub-frame and is held in a vertical position by a number of support arms bolted to the Frame. The Transfer Frame is attached to the Low Level Transfer Trolley by a combination of bolts and shear pins.

The combination of LLTT, Transfer Frame, sub-frame and a MRC is known as a Nuclear Transport Package (NTP).

The design basis vehicle impact accident specifies a collision from a 20 tonne vehicle travelling at 20 mph from any direction. In order to satisfy the safety functional requirements, the NTP is required to meet the following conditions:

- The NTP should not overturn as a complete assembly following the impact.
- The Transfer Frame should not detach from the LLTT, and with the attachments remaining within the Level D stress limits specified in the ASME Boiler and Pressure Vessel Code Section 3.
- The MRC should be shown to withstand any potential impacts of the vehicle in the event of failure of any of the frame members.
- The frame must not transmit as a result of the vehicle impact, to either container, loads that would compromise their shielding and containment boundaries.

The performance of the NTP was substantiated by finite element (FE) analysis, using the explicit non-linear transient code LS-DYNA. The work formed part of the site license application for the D154 facilities.

2. Modelling of the vehicle

The model of the vehicle is shown in Figures 1. Details of the model in the front end of the HGV are shown in Figures 2 and 3.

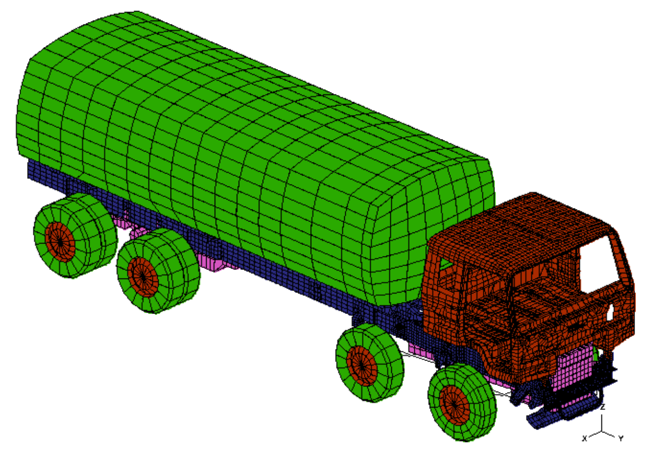

Figure 1: FE Model of the HGV

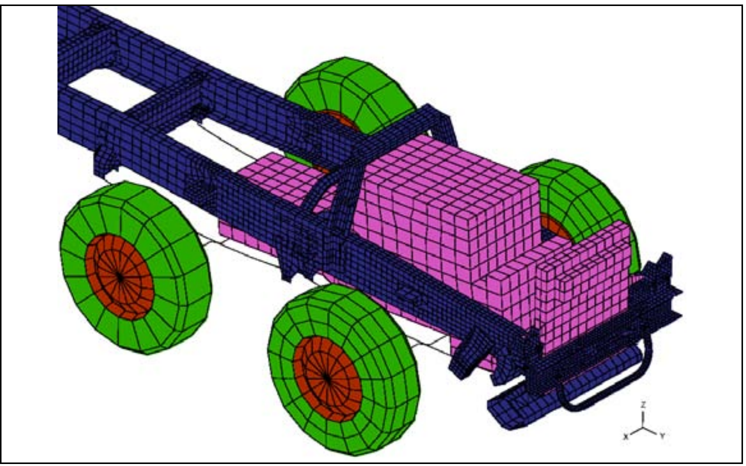

Figure 2: Details at the front of the HGV (cab not shown)

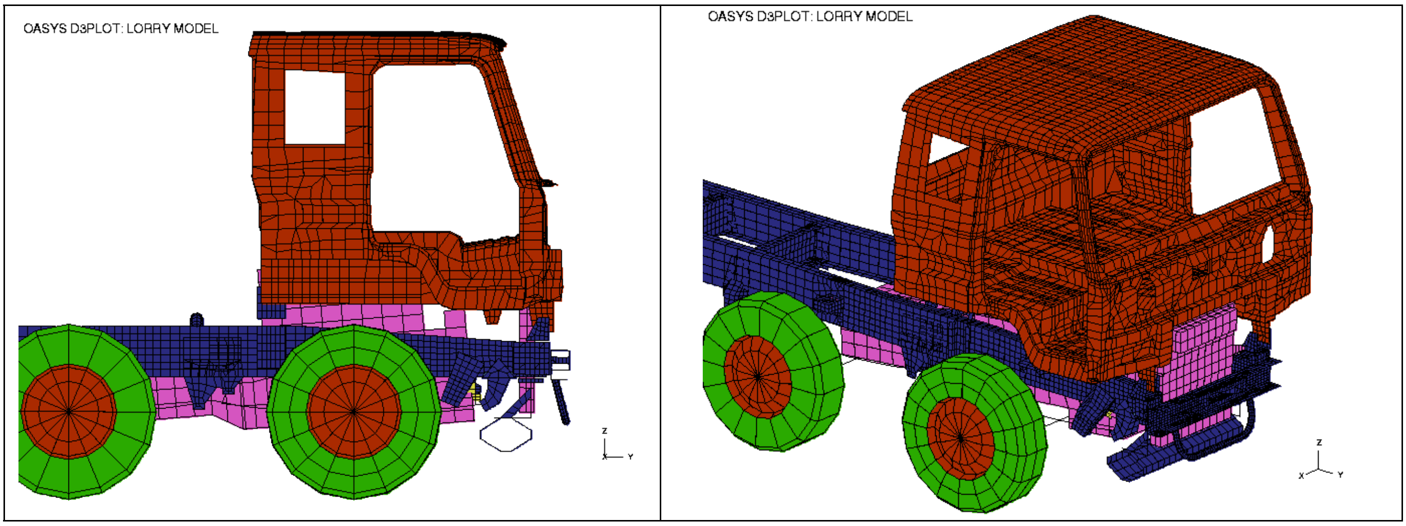

Figure 3: Details of the front end of the HGV model (Tank not shown)

Only heavy goods vehicles (hereafter HGVs) with a 6x4 or a 8x4 axle configuration can satisfy the weight requirement of the design basis vehicle impact accident. The FE model was based on an existing model of a Leyland DAF 8x4 Rigid Tanker which was originally built to study the impact behaviour of highway structures from vehicle collisions. It was validated by correlation with a collision test.

A survey of HGVs with a 8x4 and a 6x4 axle configuration indicated that the Leyland DAF was typical and representative in terms of chassis weight, chassis spacing, chassis height, chassis frame section and front overhang - the characteristics of the HGVs that are most relevant for the present impact scenarios.

The structure of the HGV consisted mainly of two chassis rails upon which the suspension, drive-train, cab and tank were mounted. The chassis rails had a 298x86x8mm channel section. The majority of this structure was modelled using thin-shelled elements except for the following:

- Various parts of the drive train (engine, gearbox etc) were modelled with undeformable solid elements. They were extremely strong compared with the rest of the HGV and NTP structure and they were expected to deform little.
- Axles and suspension systems were modelled using beams elements with joints and spring/damper elements modelling the suspension connections.
- The radiator was modelled with a combination of solids, springs and dampers to achieve the appropriate crush behaviour.
- The front tyres were modelled with elastic thin shells with an “airbag” defined for the interior to represent the tyre pressure of about 22psi.
- The engine-gearbox was mounted at its front and rear to the chassis rails. The connections were modelled with springs with failure loads.
- The lorry cab was mounted at the front on both sides to the chassis rails. At the back, it was mounted from the centre to the chassis rail via a “bridge” structure that spans over the engine block. These mountings were modelled using stiff springs with appropriate failure loads.
- Structural connections in the chassis structure were all bolted connections. In the front of the HGV, these connections were modelled with springs with appropriate failure loads. Away from the impact area, these connections were modelled as fully continuous.

3. Modelling of the NTP

The model of the NTP is shown in Figure 4. Further details of the side of the NTP for impact by the HGV, and details of the gate hinge are shown in Figures 5 and 6 respectively.

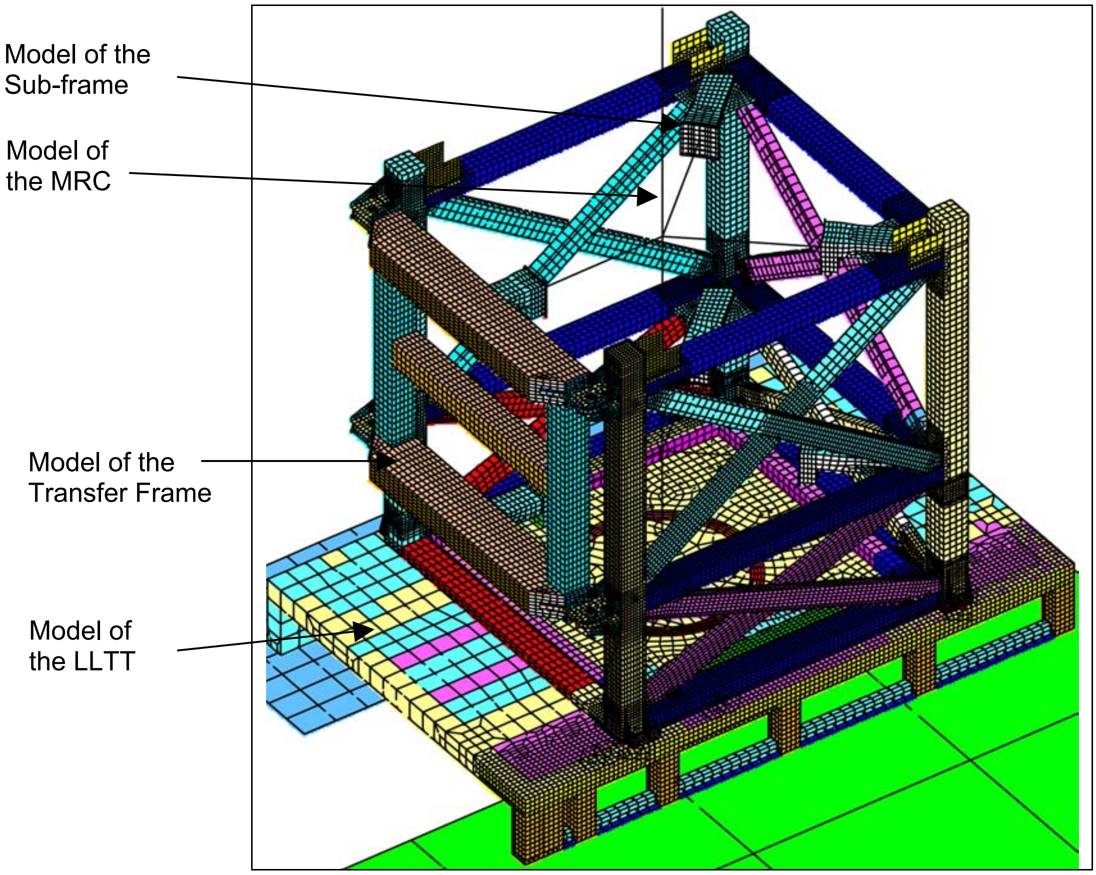

Figure 4: FE model of the NTP

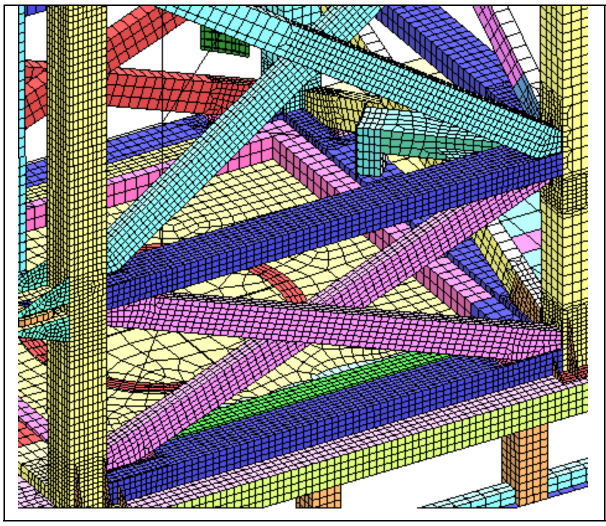

Figure 5: Close-up view of the side of the NTP for impact by the HGV

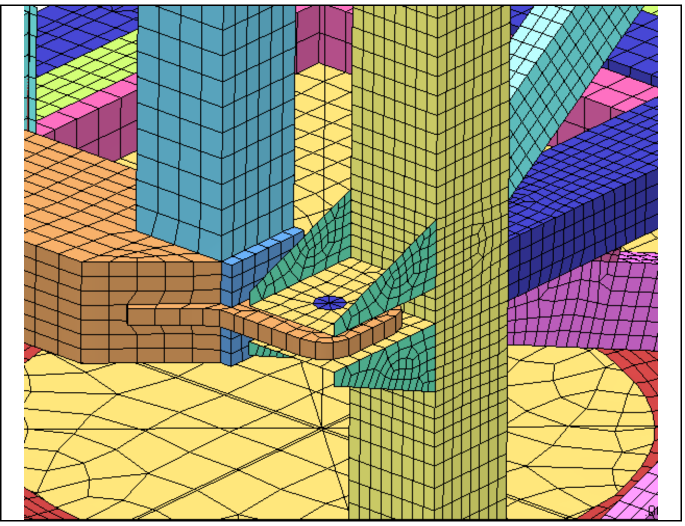

Figure 6: Close-up view of the gate hinge of the Transfer Frame model

The LLTT chassis was modelled with thin shell elements. A finer mesh was used in the areas of impact and a coarser was used elsewhere. All the welds were assumed to be “full strength” and the meshes were made continuous across the welds. This is a sufficient assumption as none of the welds were highly stressed in the impacts. The bogie and the suspension were modelled using a combination of beams and springs.

The transfer frame was explicitly modelled using thin shell elements with a finer mesh in the areas of impact. The gate hinge plate and the hinge end plate were modelled using fully integrated solid elements. The gate hinge pins were modelled using joint elements and the gate locking pins were modelled using springs. The gate was assumed to be in it’s closed and locked position. All the welds were considered to be “full strength” and so the mesh was continuous across the welds.

The frame is mounted onto the LLTT via a bracket at each of the column posts, with an M45 bolt and an M42 bolt. Each connection was modelled using a set of three springs, one acting vertically for the tensile connection and two acting horizontally for the shear connection.

Considering that the MRC was not directly impacted in any of the scenarios, and it was a significantly stiffer structure than the rest of the NTP, it was not necessary to model the MRC explicitly. It was modelled instead, with a set of rigid beams, and was given the correct mass, location of centre of gravity and inertia properties. The base was modelled with a ring of shell elements so that its interface with the sub-frame and the LLTT could be appropriately simulated.

4. Impact Scenarios

Three impact scenarios were identified as the worst scenarios to cause overturning of the NTP. They are as follows and shown in Figures 7 to 9 below:

Scenario 1	Mid-Side Impact	Impact of the HGV on the side of the NTP with the vehicle being central between the two nearside frame columns
Scenario 2	Corner-Side Impact	An impact of the HGV on the side of the NTP but this time positioned centrally with respect to the nearside column nearest the frame gate
Scenario 3	Angled-Corner Impact	An impact of the HGV hitting the nearside frame corner, nearest the gate, at a 45 degree angle

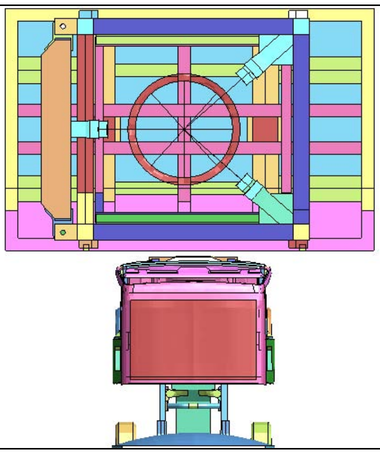
Figure 7: Scenario 1

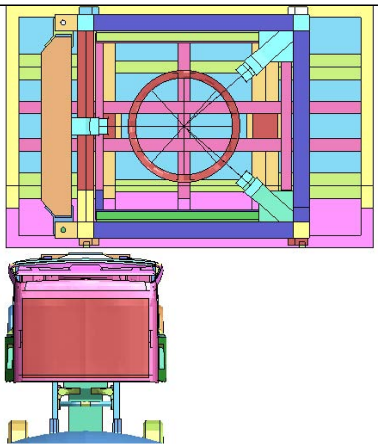
Figure 8: Scenario 2

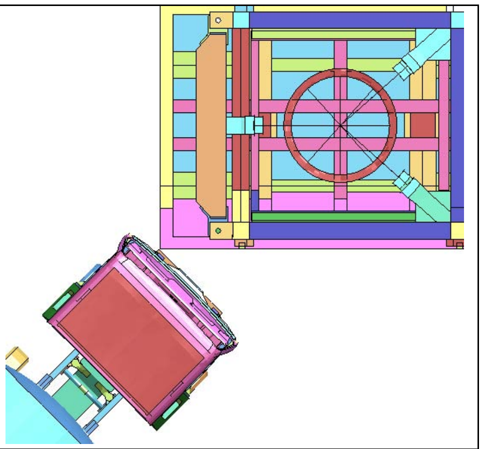
Figure 9: Scenario 3

5. Initial Conditions

It was important that the weight of the Transfer Frame, the sub-frame and the MRC was acting on the LLTT at the beginning of impact. Each analysis therefore consisted of two phases, a dynamic relaxation phase during which the weight (under gravity) was allowed settle onto the LLTT, followed by a transient phase during which the impact was simulated. At the beginning of the transient phase, the HGV was located close to the NTP in an orientation and location depending on the impact scenario and was given an initial velocity of 20mph in the direction towards the NTP.

6. Evaluation Methodology

Integrity of the steel structural members in the Transfer Frame structure was evaluated by comparing the plastic strains at the end of the analysis at the top, middle and bottom integration points of the shell elements against the minimum necking strain of the material (18%) as specified in the material standards.

To assess the integrity of the welds in the Transfer Frame, the plastic strains in the elements adjacent to the welds were examined. For the full penetration welds, the weld will be stronger than the parent plates and the parent plates will accumulate the plastic strains in preference to the weld. These welds were evaluated against the allowable plastic strains of the parent material. The other welds were “full strength” welds – its total throat length was equal to or greater than the thickness of the parent material. Experience shows that in these type of impact scenarios, failure will occur in the parent material adjacent to the weld instead of in the weld itself. However, for conservatism, they were assessed using the allowable plastic strain of the weld material, at 9%, which was lower than the value for the parent material.

The assessment of the damage to the NTP concentrated on the plastic strains relevant to the overall structural integrity of the Transfer Frame members. Localised plastic strains might result in small areas of material failure but will not have a significant effect on the overall structural integrity of the Transfer Frame.

The allowable tensile load in the bolts connecting the Transfer Frame and the LLTT was based on the stresses not exceeding 0.7 times the ultimate stress of the material. The allowable shear load in the shear pins was based on the stress not exceeding 0.42 times the ultimate stress of the material. The allowable capacity was calculated as 0.73MN in tension and 2.3MN in shear. The forces in the springs representing the Transfer Frame to chassis connections were used in assessing the performance of these connections.

The allowable shear load in the hinge and locking pins was based on the stress not exceeding 0.42 times the ultimate stress of the material for single shear. However the hinge and locking pins are in double shear, so the capacity is twice that for single shear. Therefore, the allowable shear load for the hinge/locking pins was calculated to be 1.85MN. Their integrity was assessed using spring force time histories and the peak shear force compared to the capacity of the hinge and locking pins.

Displacement and deceleration time histories of the MRC and the HGV were also examined to assess the overall dynamics of the events and the stability of the NTP.

7. Impact Behaviour in Scenario 1 – Mid-Side Impact

Deformation of the HGV and the NTP at the end of the event is illustrated in Figure 10.

Figure 10: Deformation of HGV and NTP

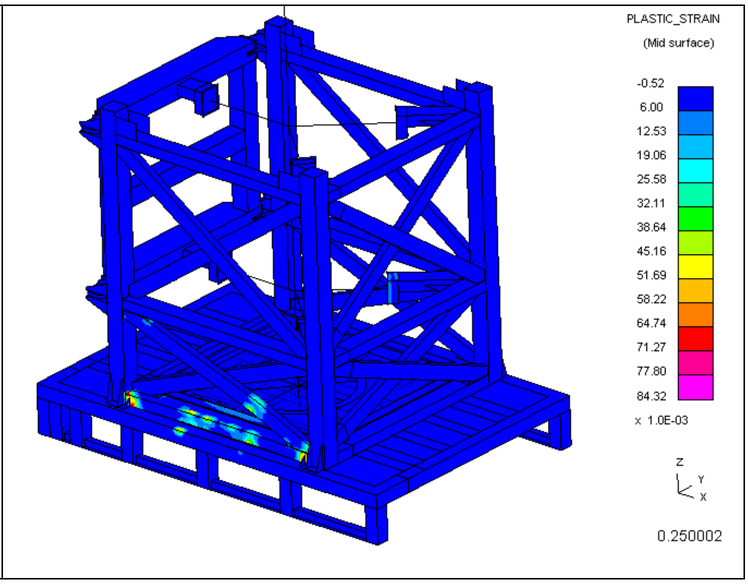

Figure 11: Plastic strains in the Transfer Frame lower bracing

There were four main load paths in this scenario. The first load path was between the channel section of the HGV chassis and the lower horizontal frame member. This resulted in significant buckling of the HGV’s channels, causing the vehicle cab to ride up onto the LLTT chassis. And as significant amount of the HGV’s momentum resided in the tank bolted to the channels, whose CG was higher than the channels, the deceleration caused the HGV to lift off at its back during the impact, as shown in Figure 12.

The second load path was between the engine block and LLTT chassis via the radiator. The third load path was between the HGV cab and middle horizontal frame member/lower bracing. The second and third load paths were less severe, with most of the deformation occurring in the HGV. The fourth load path was between the LLTT chassis and the ground/rails via the LLTT bogie and axle. This was the main load path for transferring the lateral impact load down to the ground, and it caused considerable bending in the LLTT bogie axles.

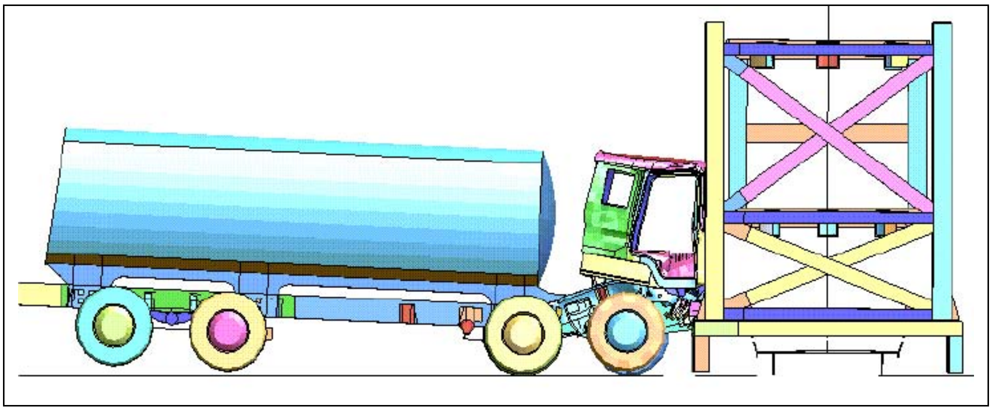

Figure 12: Lifting off at the back end of the HGV

The impact of the HGV onto the NTP occurred at a relatively low level, and caused a relatively low overturning moment which was insufficient to cause overturning of the complete assembly. The deformations of the Transfer Frame members were insufficient to cause them to contact the MRC. And no part of the vehicle penetrated the frame far enough to contact the MRC.

Plastic strains in the NTP at the end of the analysis are shown in Figure 11. The plastic strains in the structural members and the welds in the NTP remained well below the allowable values and were expected to remain intact in the impact.

Shear and tensile forces transmitted through the connections were well within the design capacity of the connections, and the Transfer Frame was therefore expected to remain attached to the LLTT and the gate of the Transfer Frame remain closed.

8. Impact Behaviour in Scenario 2 – Corner-Side Impact

Deformation of the HGV and the NTP at the end of the event is illustrated in Figures 13 and 14.

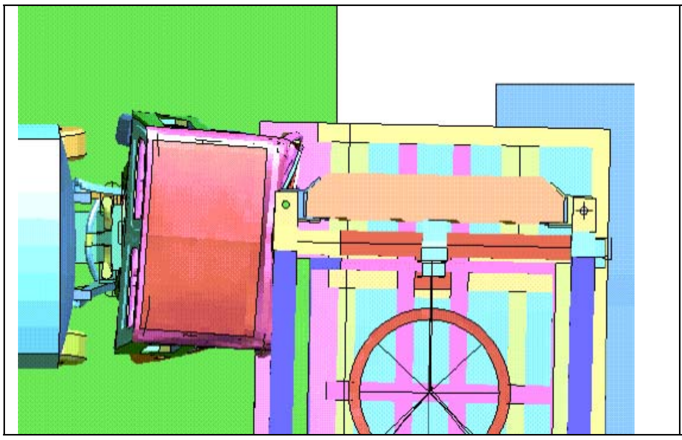

Figure 13: Deformation of HGV and NTP – view from above

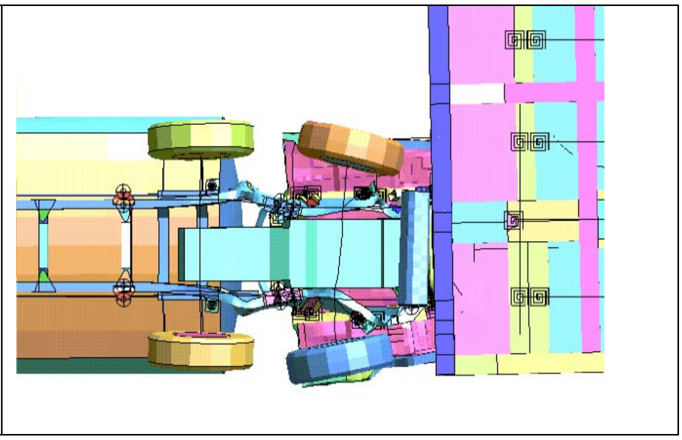

Figure 14: Deformation of HGV and NTP – view from below

There were again four main load paths. The first and most significant load path was between the right chassis rail of the HGV and the lower horizontal frame member. It caused the NTP to rotate about the vertical axis, as the impact load was concentrated at one end of the LLTT. This twisted the LLTT suspension and most of the impact load was transferred to the ground via the bogie wheels at the impacted end of the LLTT. This caused the bogie axles at the impacted end to bend, and consequently the NTP to tilt and the LLTT outriggers to make contact with the ground.

The other main load paths were between
- The engine block and the LLTT chassis via the radiator
- The HGV cab and the lower gate hinge/frame vertical column
- The LLTT chassis and ground/rails via LLTT bogie and axles.

Figure 15 shows an area in the lower horizontal frame member where one of the HGV chassis rails directed impacted, and caused large localised plastic strains. Comparison of strains on the top and bottom integration points of the elements indicated that the deformation was largely due to membrane action and therefore some localised material failure could be expected. However, this would not affect the member's overall integrity. Typical plastic strain was below the allowable strain.

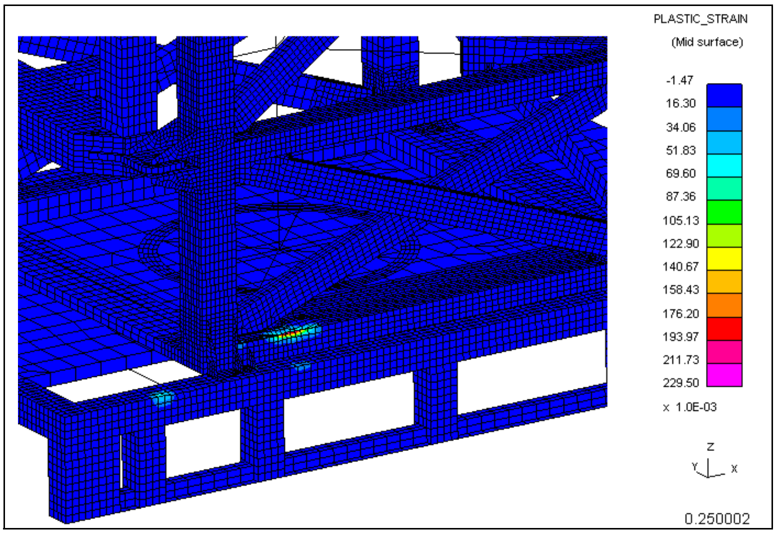

Figure 15: High localised plastic strains in the lower frame member

Although the NTP tilted more in this scenario than in scenario 1, the overall impact of the vehicle into the NTP remained at a relatively low level and did not generate sufficient overturning moment to cause the NTP to topple over. Again, the deformation of the Transfer Frame was localised and was not sufficient to come into contact with the MRC. And no part of the HGV penetrated far enough into the NTP to contact the MRC.

Shear and tensile forces transmitted through the connections were within the design capacity of the connections. The Transfer Frame was therefore expected to remain attached to the LLTT, and the gate of the Transfer Frame was expected to remain closed.

9. Impact Behaviour in Scenario 3 – Angled-Corner Impact

Deformation of the HGV and the NTP at the end of the event is illustrated in Figures 16 and 17.

There were again four main load paths in this scenario. The first load path was between the left chassis rail of the HGV and the frame-to-chassis connection bracket on the NTP, via the HGV front cross member. The angle of the impact and the geometry of the impacted areas caused the chassis of the HGV to twist. This reduced the impact loads and as a result, the overall deformation in the NTP was smaller in comparison with the other two scenarios.

The other main load paths were similar to those in the other scenarios and they were between

- The engine block and the LLTT chassis via the radiator
- The HGV cab and the lower gate hinge/frame vertical column
- The LLTT chassis and ground/rails via LLTT bogie and axles.

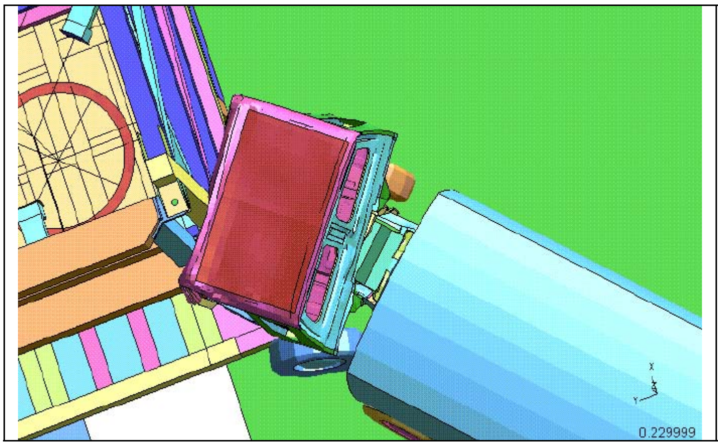

Figure 16: Deformation of HGV and NTP – view from above

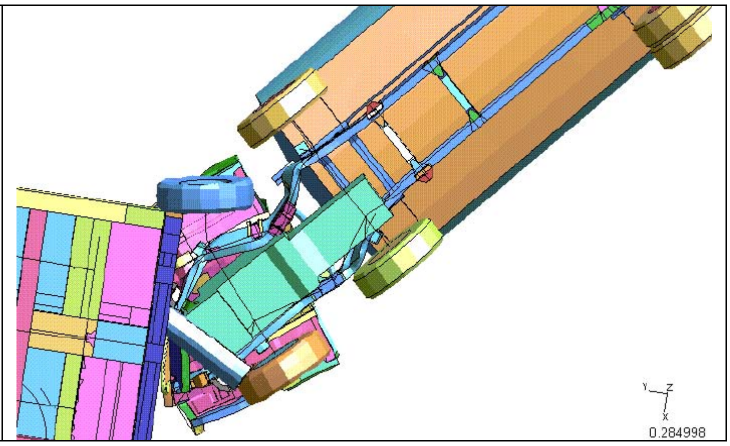

Figure 17: Deformation of HGV and NTP – view from below

One of the Transfer Frame to LLTT connection bracket was directly impacted by the HGV and very high plastic strains were seen in the bottom corner of the bracket. Although there might be some local material failure in the welds of the bracket, the overall bracket connection would remain intact. The typical plastic strains in the frame and chassis were within the allowable limits. Again, shear and tensile forces transmitted through the connections were within the design capacity of the connections. The Transfer Frame was therefore expected to remain attached to the LLTT, and the gate of the Transfer Frame was expected to remain closed.

10. Conclusions

Detailed finite element models of the NTP and the HGV were created to substantiate the performance of the NTP in the design basis vehicle impact accident. Three worst-case scenarios were identified and analysed. The analyses demonstrated that

- The impact of the HGV onto the NTP occurred at a relatively low level, and the resulting overturning moment was insufficient to cause overturning of the NTP. The NTP remained upright.
- Despite localised material failure in some areas, the Transfer Frame members and the welds remained intact.
- All shear and tensile forces transmitted through the Transfer Frame connections were within the design capacity of the connections, and therefore the Transfer Frame would remain attached to the LLTT and the gate of the Transfer Frame would remain closed during the event.
- The MRC remained intact since no part of the HGV or the Transfer Frame came into contact with it

The NTP satisfied all the safety functional requirements in the design basis vehicle impact accident.