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DEVELOPMENT OF GUIDELINES FOR DEFORMABLE AND RIGID SWITCH IN LS-DYNA SIMULATION

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DEVELOPMENT OF GUIDELINES
FOR DEFORMABLE AND RIGID SWITCH
IN LS-DYNA SIMULATION

by

Ling Zhu

A DISSERTATION

Presented to the Faculty of
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LS-Dyna simulations have been widely used in research and design to reduce fiscal and time costs. In order to improve the simulation’s efficiency, the components which experience negligible deformations are usually modeled as rigid bodies. However, the use of rigid bodies is always restricted. Though the use of more rigid bodies can save computing resources for a particular simulation, less rigid bodies are preferred for building a model in order to broaden its applications. Meanwhile, if a simulation task has multiple events, the application of rigid bodies in the particular simulation is always minimized so that it can satisfy all of the events. The restrictions of applying rigid bodies can be overcome if the components are able to switch back and forth between the rigid and deformable statuses. Currently, LS-Dyna provides several commands to switch the deformable components to rigid bodies and vice versa. However, the way of properly implementing deformable and rigid (D-R) switches has not been clarified. In order to avoid the potential issues during D-R switches and to extend the future application of D-R switches, investigations were performed herein. First, the features of each command were compared, and examples are provided to illustrate the implementations of the commands. Then, a series of simple-model investigations was performed to identify the key factors for the D-R switch. Results revealed that the D-R switch was influenced by the element choices, the inter-component connections, the boundary conditions, and the choice of the master body. Finally, based on the findings from the simple-model investigations, a procedure for applying D-R switch was developed. A couple of examples were then provided to demonstrate the benefits of using the D-R switch and to verify the proposed procedure.
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1 INTRODUCTION

1.1 Problem Statement

LS-Dyna is a general-purpose, finite element analysis code developed by Livermore Software Technology Corporation (LSTC) and used for analyzing the static or dynamic responses of structures subjected to large deformations, including structures coupled to fluid (1). Researchers have successfully used LS-Dyna in research and design to reduce time and financial cost in the past decades. More sophisticated and larger-scale finite element simulations can now be conducted due to the significant development of computer technology. However, no matter how fast the hardware has been updated, it cannot satisfy the demands to use larger and more robust models. As such, the computer technology always becomes a bottle-neck for implementing finer meshed models, and it is always demanded to maximize the current hardware capability and speed up the simulation as much as possible. One possible approach to achieve this goal is to simplify a FE model by modeling the components as rigid materials if their deformations or stresses are negligible. Compared to the deformable components, the use of rigid bodies can significantly speed up the calculation by skipping the process of checking and updating the status of each single element at every time step.

In order to improve the calculation efficiency, an LS-Dyna model is usually preferred to have as many rigid components as possible. However, it turns out that the more rigid components that are utilized, the narrower the application the model is. For the same model, the components that behave as rigid bodies in one particular simulation scenario (Scenario A) might experience significant deformations or failures in another simulation scenario (Scenario B). For example, if the model is particularly built for
Scenario A with certain components being rigid, modifications on the model are necessary before it can be used for Scenario B. An example is provided in Figure 1, the same vehicle model is used for two different simulation scenarios. Running-off a Slope (left) and Front Impact (right). The simulation of running off a slope can utilize a lot of rigid bodies to save computing time, but the front-impact simulation requires more deformable bodies to capture the vehicle’s impact behavior. The modification process could be extremely time-consuming, especially for a complicated large-scale model, which contains thousands of parts, such as an airplane, a space shuttle, a ship or a fine vehicle model (2, 3, 4, and 5). Considering the efforts and time of building these sophisticated models, it is desired to use the models with minimum modifications for as many analysis scenarios as possible once they are built. Thus, the use of rigid bodies actually hurts the simulation efficiency instead of benefiting it. Thus, less rigid bodies are preferred for modeling purposes, while more rigid bodies are preferred for calculating purposes.

Figure 1. Rigid Bodies Narrows the Model’s Application

In the mean time, if a simulation task consists of multiple events, the use of rigid bodies is always minimized in the particular simulation task. For example, a pickup truck runs off a slope and later lands on the ground surface in Figure 2. The entire simulation
basically consists of three events: (1) the vehicle runs on the upper flat ground; (2) the vehicle leaves the edge and becomes airborne; and (3) the vehicle lands on the lower ground. In order to improve the calculation efficiency, components that have negligible deformation are preferred to be modeled as rigid bodies. Therefore, the second event can have the most rigid components, followed by the first event and then the third event. However, to accurately capture the vehicle’s response, the use of rigid bodies in the simulation has to satisfy all the three events, and is minimized by the combinations of these three events. Thus, most of the components have to be modeled as deformable in this simulation, although the majority of the deformable components experience little deformation or external loads when the vehicle is airborne. LS-Dyna still checks each single element’s status even though there is no major change, which drastically slows down the simulation. So, the use of rigid bodies is compromised in the multi-event simulation, and the improvement of simulation efficiency is restricted in LS-Dyna.

Currently, LS-Dyna provides four commands that allow users to implement the switch between deformable and rigid components. These include:

(1) *DEFORMABLE_TO_RIGID;
(2) *DEFORMABLE_TO_RIGID_AUTOMATIC;
(3) *DEFROMABLE_TO_RIGID_INERTIA;
(4) *RIGID_DEFORMABLE.

If one of these cards is defined, then any deformable part defined in the model may be switched to rigid during the calculation, or from rigid to deformable. Through the use of Deformable and Rigid (D-R) switches, the restrictions of applying rigid bodies can be removed. Thus, the simulation’s efficiency can be significantly improved.
Figure 2. Vehicle Runs Off Slope

For complicated systems, a generic model can be built with all of the components being deformable initially. Based on this generic model, users can customize the implementation of rigid bodies according to their particular needs later, which can be easily achieved by including a separate D-R switching file in the generic model using the
command card “*INCLUDE.” Thus, the controversy of using less rigid bodies in modeling and using more in calculation can be solved. Meanwhile, the implementation of rigid bodies in a particular multi-event simulation can also be maximized through the use of D-R switches. All the components can be switched back and forth between rigid and deformable statuses to satisfy the needs of each individual event in the simulation task.

Although there are broad potential applications and growing demands of deformable and rigid switch, few research results are currently available for users to correctly implement the technique. Therefore, developing guidelines for using the deformable and rigid switch is necessary and practically meaningful.

1.2 Objectives

The major goal of this study was to identify the main factors that affect D-R switches and to clarify the treatments of these factors during D-R switches. Then, a guideline was developed for accurately implementing D-R switches in LS-Dyna. After obtaining the guidelines, Deformable-to-Rigid (D2R)/Rigid-to-Deformable (R2D) techniques were applied to improve current cable model developed at the Midwest Roadside Safety Facility (MwRSF) as well as the current MwRSF pickup truck model that was switched in a running-off-slope simulation to demonstrate the improvement of simulation efficiency by using D-R switches.

1.3 Scope

A literature search was first performed to understand the current D-R switch commands in LS-Dyna and to collect the available information for the implementation of these commands. Then, examples were given to illustrate the implementations and comparisons of the D-R switching commands. A series of investigations was conducted
using simple models to identify the possible key factors in D-R switches, such as element type, master body choice, original connections handling, mass change, and boundary conditions constraints during D-R switches. Based on the findings from the simple-model investigations, a guideline for implementing D-R switches was developed. To verify the proposed D-R switch procedure and demonstrate the benefits of using D-R switch, a couple of examples were given including a high-tension cable model and a C2500 pickup truck model.

1.4 Literature Research

Compared to the other main Finite Element Analysis (FEA) software, switching the component between rigid and deformable statuses is the unique feature that Dyna provide (6, 7, 8, and 9). Literature researches were performed by searching the user’s forum and the user’s conference. Limited sources of D-R switches are currently available, though there are increasing demands for implementing D2R/R2D. Most information is only available in the LS-Dyna User’s Manual (1), LS-Dyna Theoretical Manual (10), and Suri Bala’s notes (11). According to these sources, potential issues might occur during the switches between deformable and rigid components.

When a deformable body is switched to rigid, it is important to understand how the history variables are treated when the switched rigid body is restored back to its deformable state. For the node-centered variables (displacement, velocity, acceleration, etc.), the average of each node value is applied to the rigid body when a deformable body is switched to rigid. For the element-centered variables (stresses, plastic-strain, etc.), the values are internally recorded for every element with reference to the element’s local coordinate system. When the rigid body is switched back to its deformable state, the
stored element-centered variables are then re-applied to the respective elements (10, 11). Since the element history variables are stored in the local co-rotational system when deformable parts are switched to rigid, the choice of proper element type is critical during deformable and rigid switching. Elements, such as those based on Hughes-Liu, store the element history variable in the global coordinate system. Thus, structures modeled with such elements should not be applied with deformable and rigid switches (11).

The nodes on the deformable body used in a constraint definition such as *CONSTRAINED_NODAL_RIGID_BODY, *CONSTRAINED_SPOTWELD, etc., will cause instabilities during the simulation, due to the violation of the single constraint requirement on rigid bodies. To overcome this, LS-Dyna allows the user to delete or activate constraints at the time of switching, thereby making it seamless. By default, LS-Dyna internally deletes all constraints that are defined using the nodes of the deformable body before switching. Deleted constraints can be re-activated when the rigid body is switched back to its deformable state. *DEFORMABLE_TO_RIGID_AUTOMATIC provides two entries (*NRBF and *NCSF) to treat the connections in the deformable components to be switched to rigid. NBRF is used to activate/deactivate nodal rigid bodies or spot welds using either (1) *CONSTRAINED_NODAL-RIGID_BODY, (2) *CONSTRAINED_SPOTWELD, or (3) *CONSTRAINED_GENERALIZED_WELD, whose node set may use one or more of the deformable body nodes. NCSF is used to activate/deactivate constraint node sets defined using *CONSTRAINED_NODE_SET.

Later, Suri Bala pointed out in another blog note (12) that saving simulation time by switching deformable bodies to rigid bodies may not necessarily be true when using MPP-LSDYNA, because the domain decomposition routines do not account for the
additional rigid bodies that get created due to switch definitions. As a result of this, there is an increased possibility of the computationally-expensive deformable components being lumped on just a few processors while the remaining processors handle the computationally-inexpensive rigid bodies. This creates a poor load balance situation and may result in insignificant improvement in job turnaround time.

To get true performance benefits from the deformable to rigid switching, one must accompany this with a custom domain decomposition that ensures distribution of the newly created rigid bodies across ALL processors to achieve optimum load balance, as shown in Figure 3. This can be achieved by transformation of the model prior to the decomposition (using sx, sy, sz) or by using region based decomposition available in 971 versions of LS-DYNA.

![Figure 3. Illustration of Load Distribution for MPP Calculation](image-url)
It needs to be pointed out that, in LS-Dyna, the initially deformable parts can be switched to rigid and even switched back to deformable later, while the parts that are initially defined as rigid (*MAT_RIGID) in the input are permanently rigid and cannot be changed to deformable (11). However, this limitation can be overcome by initially defining parts as deformable, and immediately switching them to rigid at the beginning of the simulation.
2 D-R SWITCHING COMMANDS AND IMPLEMENTATION EXAMPLES

2.1 Current Switching Commands LS-Dyna

As previously stated, four command cards associated with deformable and rigid switches are currently available in LS-Dyna (1). They are: *RIGID_DEFORMABLE; *DEFORMABLE_TO_RIGID; *DEFORMABLE_TO_RIGID_AUTOMATIC; and *DEFORMABLE_TO_RIGID_INERTIA.

2.1.1 *DEFORMABLE_TO_RIGID

The *DEFORMABLE_TO_RIGID command switches deformable parts to rigid parts. It is a one-way switch command. In other words, once a deformable component is switched to rigid, this command cannot switch the component back to deformable. As one of the simplest switching commands, *DEFORMABLE_TO_RIGID has only two input entries: PID and MRB, as shown in Figure 4. The PID entry specifies the component that needs to be switched to rigid, and the MRB entry specifies the master body. A component can be merged with a separate master rigid body specified under MRB, or this component becomes either an independent or master rigid body if the MRB entry is set to be zero. It is noted that *DEFORMABLE_TO_RIGID can only activate a switch at the start of the simulation (Time = 0). If a switch is desired in the middle of a simulation, the *DEFORMABLE_TO_RIGID command has to be used in combination with the *RIGID_DEFORMABLE command in a restart. Each *DEFORMABLE_TO_RIGID command can only switch one component per switch. Thus, the *DEFORMABLE_TO_RIGID command has to be used repeatedly if multiple components are needed to be switched at the same time.
**DEFORMABLE_TO_RIGID**

<table>
<thead>
<tr>
<th>Variable</th>
<th>PID</th>
<th>MRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>none</td>
<td>0</td>
</tr>
</tbody>
</table>

*Figure 4. Card Format of *DEFORMABLE_TO_RIGID*

### 2.1.2 *RIGID_DEFORMABLE*

The *RIGID_DEFORMABLE* command defines parts to be switched from rigid to deformable and deformable to rigid. However, it is only used in a restart file and has to be used in combination with other switching commands. The components to be switched by the *RIGID_DEFORMABLE* command in a restart file have to be switched previously. It is not possible to perform part material switching on a restart if it was not flagged in the initial analysis. The reason for this is that extra memory needs to be set up internally to allow the switch to take place. Three options are available with *RIGID_DEFORMABLE* in the restart file: CONTROL, D2R, and R2D, as shown in Figure 5. *RIGID_DEFORMABLE* can conduct two-way switches. The option D2R switches a component from deformable to rigid, and the option R2D activates a switch from rigid to deformable.

Since nodal rigid bodies and nodal constraints are not compatible with rigid components, they might cause instabilities during deformable and rigid switches. Knowing how to deal with the nodal rigid bodies and nodal constraints is critical during deformable and rigid switches. The option of *RIGID_DEFORMABLE_CONTROL* allows users to delete or activate nodal rigid bodies through the use of the entry NRBF, and to delete or activate nodal constraint set through NCSF. Meanwhile, the input entry RWF allows the users to delete or activate rigid walls. DTMAX defines the maximum
permitted time step. Also, *RIGID_DEFORMABLE can only switch one component each time. And it can only activate the switch immediately at the beginning of the restart.

*RIGID_DEFORMABLE_CONTROL

<table>
<thead>
<tr>
<th>Variable</th>
<th>NRBF</th>
<th>NCSF</th>
<th>RWF</th>
<th>DTMAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>none</td>
</tr>
</tbody>
</table>

*RIGID_DEFORMABLE_D2R

<table>
<thead>
<tr>
<th>Variable</th>
<th>PID</th>
<th>MRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>None</td>
<td>0</td>
</tr>
</tbody>
</table>

*RIGID_DEFORMABLE_R2D

<table>
<thead>
<tr>
<th>Variable</th>
<th>PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>none</td>
</tr>
</tbody>
</table>

Figure 5. Input Entries of Three Options of *RIGID_DEFORMABLE

2.1.3 *DEFORMABLE_TO_RIGID_AUTOMATIC

Compared to the aforementioned commands, the command of *DEFORMABLE_TO_RIGID_AUTOMATIC has more input entries, as shown in Figure 6. It provides more choices for deformable and rigid switches. This command can perform two-way switches, which allows deformable parts to be switched into rigid and also lets them be switched back to deformable later by specifying the input entry R2D or D2R. Besides, instead of one component each time, multiple parts can be switched by *DEFORMABLE_TO_RIGID_AUTOMATIC at the same time.
*DEFORMABLE_TO_RIGID_AUTOMATIC

<table>
<thead>
<tr>
<th>Variable</th>
<th>SWSET</th>
<th>CODE</th>
<th>TIME1</th>
<th>TIME2</th>
<th>TIME3</th>
<th>ENTNO</th>
<th>RELSW</th>
<th>PAIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>none</td>
<td>0</td>
<td>0</td>
<td>1.0E20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>NRBF</th>
<th>NCSF</th>
<th>RWF</th>
<th>DEMAX</th>
<th>D2R</th>
<th>R2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>none</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Card Format of Command *DEFORMABLE_TO_RIGID

The *DEFORMABLE_TO_RIGID_AUTOMATIC command also offers more flexible approaches to activate a switch. A switch can be activated in three ways: time, rigid wall force, and contact surface force. Three time-control input entries are available: TIME1, TIME2, and TIME3. By specifying corresponding time entries, a switch can take place or stop anytime during the simulation. TIME1 defines the starting time of a switch; TIME2 defines the stop time of a switch; and TIME3 defines the delay period such that another automatic switch will not happen immediately after this switch.

A switch can be triggered by contact force and rigid wall force using the combination of entries CODE and ENTNO. The input of CODE defines whether the switch is controlled by rigid wall or contact surface force, and the entry of ENTNO specifies the rigid wall or contact surface IDs. If CODE is defined as 1, the switch takes place between TIME1 and TIME2 when rigid wall force is zero. If CODE is defined as 2, the switch takes place between TIME1 and TIME2 when contact surface force is zero. If CODE is defined as 3, the switch takes place between TIME1 and TIME2 when rigid wall force is non-zero. If CODE is defined as 4, the switch takes place between TIME1 and TIME2 when contact surface force is non-zero. However, the contact control option doesn’t work with all contact types. Only certain contact commands can be used with this
contact controlled switch. An illustration of different switching activations in
*DEFORMABLE_TO_RIGID_AUTOMATIC is shown in Figure 7.

In *DEFORMABLE_TO_RIGID_AUTOMATIC, two related switches can be
paired up by the input entry of PAIRED. This makes it possible for a component to
automatically switch back and forth between deformable and rigid according to the change
of rigid wall force or contact surface force. To achieve this, one switching set is defined as
master and the other is defined as slave. The activation of the slave switch relies on the
master switch.

Another helpful feature of *DEFORMABLE_TO_RIGID_AUTOMATIC is its
ability to deal with connections/constraints. To avoid the instabilities caused by nodal
rigid bodies or nodal constraints, *DEFORMABLE_TO_RIGID_AUTOMATIC allows
users to delete/ reactivate them through the use of NRBF and NCSF.
Figure 7. Switch Activation in *DEFORMABLE_TO_RIGID_AUTOMATIC
2.1.4 *DEFORMABLE_TO_RIGID_INERTIA

The *DEFORMABLE_TO_RIGID_INERTIA card allows inertial properties to be defined for deformable parts that are to be swapped to rigid at a later stage. It is also a one-way switch.

Component inertia is usually determined in two ways in LS-Dyna: one is calculated based on the component meshing; the other is manually defined by users. During deformable and rigid switches, if various components are merged together, LS-Dyna will re-compute the new rigid body properties from the overall merged meshing by default. Since the meshing density of each component usually varies from each other, the recalculation of the inertia from the overall merged meshing might be different from the pre-merging status. This issue can be overcome by the use of *DEFORMABLE_TO_RIGID_INERTIA. However, when rigid bodies are merged to a master rigid body, the inertial properties defined for the master rigid body apply to all members of the merged set.

2.2 Implementation Examples

Though descriptions of each command entry are available in the user’s manual (1), it could still be confusing for users to correctly implement those commands without specific examples to reference. Few examples are publically available to instruct users on the implementation of switching commands, except one using the combination of the *DEFORMABLE_TO_RIGID command and the *RIGID_DEFORMABLE command provided by Reid in the LS-Dyna example manual (13). In order to illustrate the implementation and features of each switching command, a series of switching examples are developed based on Reid’s model and are tailored for this particular application. Five models are presented herein, including a baseline model and four different switching models, as shown in Table 1.
Table 1. List of Deformable and Rigid Switching Examples

<table>
<thead>
<tr>
<th>Models Feature</th>
<th>Baseline</th>
<th>Example I</th>
<th>Example II</th>
<th>Example III</th>
<th>Example IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deformable throughout</td>
<td>Manually Switch</td>
<td>Time-Control Automatic Switch</td>
<td>Contact Force-Control Automatic Switch</td>
<td>Paired Contact Force-Control Automatic Switch</td>
</tr>
</tbody>
</table>

2.2.1 Baseline Model

The baseline scenario is a collision of two pendulums. Two spheres are connected to wires to form two pendulums. One sphere is in a horizontal position with gravitational acceleration, base acceleration, and is given an initial velocity in the vertical direction. The other sphere is in the vertical direction. The system is illustrated in Figure 8, and its complete deck file, sans nodes and elements, is provided in Appendix A.

Figure 8. Illustration of the Pendulum Collision

The whole simulation last 25 ms, and the collision occurred around 22 ms. It took 71007 seconds (19 hours 43 minutes 27 seconds) to run the baseline, model (10800 shell elements)
using one cpu on the HOMESTEAD cluster at the University of Nebraska-Lincoln. To reduce the simulation time, the spheres are to be treated as rigid bodies while no contact or deformation occurs, and are switched to deformable during contact. Several examples are presented herein to show the various deformable and rigid switching approaches and the implementation of each switching command in LS-Dyna. To be consistent, all of the examples were run with one cpu on the HOMESTEAD computer at the University of Nebraska-Lincoln.

2.2.2 Example I

The deformable and rigid switch was first conducted by the use of

*DEFORMABLE_TO_RIGID in combination with *RIGID_DEFORMABLE_R2D. The simulation has to be split into two separate stages, since both *DEFORMABLE_TO_RIGID and *RIGID_DEFORMABLE_R2D can only start the switch at the beginning of a calculation. In the first stage, the command of *DEFORMABLE_TO_RIGID is added to the baseline deck, as shown in Figure 9, requesting the two originally deformable spheres to be switched to rigid immediately at the beginning of the calculation. It was noted that the command of *DEFORMABLE_TO_RIGID was used twice in order to switch both part 1 and part 2 into rigid, since it can only switch one component at a time. Then, the calculation is suspended before the impact happens by modifying the termination time from 30 ms to 21 ms.

*DEFORMABLE_TO_RIGID
$     PID     MRB
1
*DEFORMABLE_TO_RIGID
$     PID     MRB
2
$

Figure 9. Input Illustration of *DEFORMABLE_TO_RIGID

In the second stage, the calculation is restarted using a restart file. The restart file consists of the command of *RIGID_DEFORMABLE_R2D requesting the two spheres to be switched back to deformable and a new terminating time of 30 ms, as shown in Figure 10. Similar to
*DEFORMABLE_TO_RIGID, two *RIGID_DEFORMABLE_R2D are used to switch both Parts 1 and 2 back to deformable.

```
*KEYWORD
$  
*CONTROL_TERMINATION
$  ENDTIM  ENDCYC  DTMIN  ENDENG  ENDMAS
30
$
*RIGID_DEFORMABLE_R2D
$  PID
  1
$
*RIGID_DEFORMABLE_R2D
$  PID
  2
$
*END

Figure 10. Restart File of Example I
```

In the baseline model, it took 56,623 seconds (15 hours 43 minutes 43 seconds) to simulate the horizontal sphere’s 21-ms drop in the first stage, while it took only 33 seconds after the spheres were switched to rigid, and the total calculation time was reduced from 71,007 seconds (19 hours 43 minutes 27 seconds) to 11,642 seconds (3 hours 14 minutes 52 seconds).

2.2.3 Example II

The switch can also be performed automatically without the hassle of manually stopping and restarting the simulation. This can be achieved through the use of command *DEFORMABLE_TO_RIGID_AUTOMATIC. There was no need to split the process into two stages, and all the operations can be finished in one file. The complete switch consisted of two switching sets. As shown in the top of Figure 11, switching set 1 requested the simulation to switch parts 1 and 2 into rigid at time zero by setting TIME1 as zero and by specifying the total number of components to switch under D2R. It was noted that D2R only indicates how many components were to be switched but not the specific component IDs. The entire particular
component IDs were listed afterwards. This feature allows *DEFORMABLE_TO_RIGID_AUTOMATIC to switch multiple components at the same time. In this case, $D2R$ is set to “2” and part IDs 1 and 2 were listed afterwards. No master body was specified, which meant both parts 1 and 2 would be treated as separate rigid bodies after the switch.

The switching set 2 (the bottom of Figure 11) requested the simulation to switch parts 1 and 2 back to deformable at time 21 ms before the collision happens by setting $TIME1$ to “21” and $R2D$ to “2”. The activation of switch set 2 was automatically carried out by LS-Dyna when the simulation progress came to 21 ms.

The total calculation time for Example II was 11433 seconds (3 hours 10 minutes 33 seconds).

<table>
<thead>
<tr>
<th>*DEFORMABLE_TO_RIGID_AUTOMATIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SWSET$</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>$NRBF$</td>
</tr>
<tr>
<td>$ParID$</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

Figure 11. Input Sample of Time Controlled Automatic Deformable and Rigid Switch

2.2.4 Example III

Besides the time controlled switch in Example II, an automatic switch can also be activated by the contact force between the two spheres. However, it is noted in the user’s manual (1) that only surface to surface and node to surface contacts can be used to activate automatic switch. Thus, in this case, *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID was used in lieu of the commonly used *CONTACT_AUTOMATIC_SINGLE_SURFACE, as shown
in Figure 12. The ID option in contact definition is highly recommended to indicate the contact ID, which was to be used as the input for ENTNO in the command of *DEFORMABLE_TO_RIGID_AUTOMATIC.

![Image of code snippet]

**Figure 12. Input of *CONTACT_SURFACE_TO_SURFACE_ID**

Then, two sets of *DEFORMABLE_TO_RIGID_AUTOMATIC were used, as shown in Figure 13. The first one was to switch the two spheres into rigid when there was no contact force between the two spheres, which occurred immediately at the beginning of the simulation. To achieve this goal, the entry of CODE is defined as “2,” and the entry of ENTNO was defined as “99,” which was the contact ID of the two spheres defined by the contact command. D2R was specified as 2 and all the rest entries are left as default.

The second switching set was to immediately switch the spheres back to deformable when the contact force between the spheres was non-zero. The input of CODE was set to “4” and R2D was set to “2.” The same contact ID “99” was still used for ENTNO, and all the other entries were left as default.

The total calculation time for Example III was 3848 seconds (1 hour 4 minutes 8 seconds)
2.2.5 Example IV

As shown above, the features of time control and contact control have made it convenient to switch the model automatically. However, the two switching sets in Example III were isolated from each other. Each switching set only took place once and would not be activated again, even when the contact criterion was met later. In other words, the spheres would not be switched to rigid after the collision even if the contact force was zero again. The model could be further accelerated if the spheres were switched to rigid again after they bounce off each other and switch back to deformable only when contact happens. This goal can be fulfilled through the use of the entry of $PAIRED$ to pair up the two opposite contact-control switches.

The pair-up example (Example IV) was based on the two contact-control switching sets in Example III. One set needs to be defined as the master set, and the other needs to be defined as the slave. The slave switch will not take place until the master set happens. In this case, switching set 1 is defined as the master by specifying its entry of $PAIRED$ to “1,” and switching set 2 is the slave by setting its entry of $PAIRED$ to “-1.” Meanwhile, these two sets have to be related to each other by setting its own entry of $RELSW$ as the other’s switch set ID, as shown in Figure 13. Input Sample of Contact Controlled Deformable and Rigid Switch

Figure 13. Input Sample of Contact Controlled Deformable and Rigid Switch
Figure 14. A similar example is also available in LS-Dyna User’s Manual (1) to illustrate the implementation of *PAIRED*.

The total calculation time for Example IV was 411 seconds (6 minutes 51 seconds).

*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code timed1 timed2 timed3 entno relsw paired
  1 2 99 2 1
$ nrdf nccsf rwf dtmax D2R R2D

$ ParID master
  1
  2

*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code timed1 timed2 timed3 entno relsw paired
  2 4 99 1 -1
$ nrdf nccsf rwf dtmax D2R R2D

$ ParID master
  1
  2

$ Figure 14. Sample of Implementing PAIRED

2.2.6 Example V

Energy histories of baseline model and different switched models are compared in Figure 15. It is clearly shown that the kinetic energy was increased when the spheres were switched to rigid bodies. The difference is a result of the changed mass and inertia during D2R switch, which will be discussed in later chapters. To fix this problem, the mass and inertia of the spheres after D2R switching need to be maintained as before switching, which can be achieved through the use of *DEFORMABLE_TO_RIGID_INERTIA*. The mass and inertia of the spheres are defined as the original values before switching to rigid, as shown in Figure 16. Corresponding results are shown in Figure 17. By manually defining the new rigid bodies’ mass and inertia, the inaccurate energy change was fixed. The total calculation time for Example V was the same as Example I.
Figure 15. Kinetic Energy Change Caused by D2R Switches

*DEFORMABLE_TO_RIGID_INERTIA
$    PID
  1
$    XC    YC    ZC    TM
-0.99E+02  -0.49E+01  0.49E+01
$    IXXX   IXY   IXZ   IYY   IYZ   IZZ
  0.24E-01   0.75E-05  0.85E-06  0.24E-01  -0.96E-06  0.24E-01
$
$
*DEFORMABLE_TO_RIGID_INERTIA
$    PID
  2
$    XC    YC    ZC    TM
  0.15E+02    0.99E+02  0.49E+01
$    IXXX   IXY   IXZ   IYY   IYZ   IZZ
  0.24E-01  0.15E-06  -0.16E-06  0.24E-01  0.89E-07  0.24E-01
$

Figure 16. Input Examples of *Deformable_To_Rigid_Inertia
2.2.7 Conclusion and Summarization

Any deformable part can be switched to rigid through the use of the switching commands in LS-Dyna. However, parts that are initially defined as rigid (*MAT_RIGID) in the input are permanently rigid and cannot be changed to deformable. Among these commands, *DEFORMABLE_TO_RIGID is the simplest to implement, but it can only perform one-way switches, and has to start switching at time zero. *RIGID_DEFORMABLE also has simple inputs. It can perform two-way switches, but it is only used in a restart file and can only switch the components previously switched at time zero. *DEFORMABLE_TO_RIGID_AUTOMATIC has more flexibility to conduct deformable and rigid switches, which can activate the switches in various ways.

The functions of each of the switching commands are presented through a series of examples of a two-pendulum collision model. Several different switching approaches are conducted, and the results are compared and summarized in Figure 18 and Table 2. It is clearly shown by the results that the deformable and rigid switches can significantly improve the calculation efficiency. The trajectories of Examples I through IV were slightly different from the baseline model due to the mass change errors; while Example V showed a good agreement with
the baseline model after correcting the mass error. Considering that the string mass herein was exaggerated, the mass increase should be insignificant for the normal pendulums when the string mass is trivial compared to the ball mass.

Table 2. Summary of Various Pendulum Switching Examples

<table>
<thead>
<tr>
<th>Run</th>
<th>Baseline</th>
<th>Example I</th>
<th>Example II</th>
<th>Example III</th>
<th>Example IV</th>
<th>Example V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation Time (sec)</td>
<td>71007</td>
<td>11692</td>
<td>11433</td>
<td>3848</td>
<td>411</td>
<td>11692</td>
</tr>
<tr>
<td>Reduced Time</td>
<td>NA</td>
<td>85%</td>
<td>84%</td>
<td>95%</td>
<td>99.5%</td>
<td>85%</td>
</tr>
<tr>
<td>Switch Activation</td>
<td>NA</td>
<td>Manual</td>
<td>Time</td>
<td>Contact Force</td>
<td>Contact Force</td>
<td>Manual</td>
</tr>
<tr>
<td>Automatic Switch</td>
<td>NA</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Figure 18. Trajectories Comparison between Various Switching Examples
3 ELEMENT CHOICES FOR DEFORMABLE AND RIGID SWITCH

3.1 Introduction

During a deformable-rigid switch, when a deformable component is switched to rigid, there is no more stress/strain change until this component is switched back to deformable again. To make a model switchable, the model should be able to accurately store pre-rigid status and retrieve it when the model is about to be switched back to deformable later. In fact, how a model stores and retrieves its pre-rigid status is closely related to the element formulation that the model uses. Since various element options are available in LS-Dyna and each element has its unique algorithm, certain element types might not be suitable for deformable-rigid (D-R) switches. Therefore, the proper choice of element formulation is very critical for a proper D-R switch.

It is noted in Suri’s notes (11) that Hughes-Liu shell element (Type 1) might present inaccurate behavior after switching back to a deformable body from the rigid status. Because the calculation of Hughes-Liu shell element is derived in a global coordinate system. If any rotational movement occurs during the object’s rigid stage, the stress and strain status stored before the rigid switch will be disturbed, and it will no longer be valid for the new position when the component is switched back to deformable again. Thus, the Hughes-Liu shell element (Type 1) is not recommended in models that might perform D-R switches.

Besides shell elements, beam and solid elements are also widely used in LS-Dyna simulation, but little information is available about beam elements and solid elements’ D-R switchable performance. Therefore, a comprehensive investigation of elements’ compatibility with deformable-rigid switching is practically meaningful. An investigation
of the element compatibilities with deformable and rigid switches is conducted herein in order to provide a guideline of element choice for implementing deformable and rigid switches. The investigation covers most of the commonly used element types in LS-Dyna, including beam elements (1-D), shell elements (2-D), and solid elements (3-D).

### 3.2 Beam (1-D) Element

Due to their simplicity, 1-D elements are commonly used in LS-Dyna to model beam structures, springs, spot-welds, belts, etc. Three commonly used 1-D element types are selected in this section for the D-R compatibility investigation: Hughes-Liu (HL Type 1) beam element (LS-Dyna default option); Belytschko-Schwer (BS Type 2) beam element; and Truss (Type 3) element.

Two testing scenarios were designed to investigate the compatibility of 1-D elements and D-R switching. Scenario 1 only performed translational movement and kept all of the vector directions intact throughout the simulation, while scenario 2 combined rotational movement. Each scenario was run with a pure-deformable baseline model and a D-R switch model.

#### 3.2.1 Test Scenario 1

Test scenario 1 was designed as a single beam element with a length of 10 mm being stretched at both ends using prescribed nodal displacement, as shown in Figure 19. The beam was modeled with a pure elastic material (MAT_ELASTIC). The entire simulation ran for 20 ms. Cross-section force and internal energy of the beam were recorded to indicate the beam’s deformation status.
Figure 19. Illustration of Beam Element Baseline Model - Test Scenario 1

In the baseline model, the beam was deformable throughout the simulation, and the corresponding results are shown in Figure 20 and Figure 21. The cross-section force of all three beam elements increased linearly, and their internal energies also increased correspondingly.

Figure 20. Cross-Section Force Comparison of Baseline Model Beam - Test Scenario 1
Then, in order to test the beam element’s performance during deformable-rigid switching, the model was run with the beam being switched to rigid between 10.5 and 14.5 ms. Corresponding results of the D-R model of Testing Scenario 1 are plotted in Figure 22 and Figure 23. It was clearly shown in Figure 22 that, for all three beam elements, the cross-section force linearly increased until the beam became rigid at 10.5 ms. Then, the cross-section force was maintained at a constant value as long as the beam was rigid. After the beam was switched back to a deformable body at 14.5 ms, the cross-section force proceeded to increase along the same trend as before. Meanwhile, the internal energy dropped to zero when the beam was rigid, but the pre-rigid energy level was retrieved and continued to develop as normal after the beam was deformable again. It seems all three beams can be switched to rigid and can be switched back to deformable smoothly in Testing Scenario 1.
Figure 22. Cross-Section Force Comparison of Switched Beam - Test Scenario 1

Figure 23. Internal Energy Comparison of Switched Beam - Test Scenario 1
3.2.2 Test Scenario 2

In Test Scenario 1, because the beam element performed translational movement, the directions for the stress and strain vectors were the same before and after the beam’s rigid period. To further investigate the beam element’s compatibility with D-R switches, rotational movement was introduced in Test Scenario 2. In Test Scenario 2, the beam element was stretched laterally until 10 ms; then the stretch was stopped. Between 10 ms and 15 ms, the beam’s deformation was held and the beam rotated 90 degrees. At 15 ms, the rotation was stopped and the beam started to stretch vertically until the end of the simulation. Illustration of Testing Scenario 2 is shown in Figure 24. The cross-section force and internal energy of Test Scenario 2 baseline model for all three beam types are plotted in Figure 25 and Figure 26.

![Figure 24. Illustration of Beam Element Baseline Model-Test Scenario-2](image-url)
Figure 25. Cross-Section Force Comparison of Baseline Beam - Test Scenario 2

Figure 26. Internal Energy Comparison of Baseline Beam - Test Scenario 2
Then, Test Scenario 2 was re-run with D-R switches included. During the rotation, the beam was switched to a rigid body at 10.5 ms and was switched back to deformable body at 14.5 ms. Because of the rotation, the vector directions of stress and strain were changed at the time when the beam was switched back to deformable body. The results from all three beam elements are plotted in Figure 27 and Figure 28. Although all of three beam elements could be smoothly switched to a rigid body during rotation, none of the beams could accurately retrieve the pre-rigid statuses, and none could either behave normally after switching back to a deformable body. Thus, none of the selected beam elements are recommended for D-R switch when any rotational movements might be involved.

![Figure 27. Cross-Section Force Comparison of Switched Beam - Test Scenario 2](image-url)
3.2.3 1-D Element Summary

Two scenarios were designed to test beam elements’ behavior during the D-R switch. Three commonly used beam elements (Types 1, 2, and 3) were tested in both scenarios. The results revealed that all of the beam elements can accurately store pre-rigid status when they were switched to rigid bodies. D-R switching did not affect beam elements’ performance when no rotational movements occurred, and all the beam elements could accurately retrieve this status when they were switched back to deformable. However, if any rotational movement occurred, none of the beams could accurately retrieve its pre-rigid status when it was switched back to deformable. Therefore, beam elements should not be involved in D-R switching unless there is absolutely no rotational movement.
3.3 Shell (2-D) Element

Shell elements are the most used element type in LS-Dyna modeling due to its efficiency and simplicity. Similar to the beam element, two test scenarios were designed to evaluate shell elements’ compatibility with D-R switch. Several commonly used shell elements were selected for the investigation, including both reduced integrated and fully integrated shell elements, as shown in Table 3.

Among these shells, Hughes-Liu (Type 1) is the first shell element embedded in LS-Dyna; Full-integrated elements are often used to avoid hourglassing problem; Belytschko-Tsay (Type 2) was implemented in LS-DYNA as a computationally efficient alternative to the Hughes-Liu shell element. Because of its computational efficiency, the Belytschko-Tsay shell element is usually the shell element formulation of choice. For this reason, it has become the default shell element formulation for explicit calculations (15).

<table>
<thead>
<tr>
<th>Table 3. Selected Shell Element Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected Reduced Integrated Shell Types</td>
</tr>
<tr>
<td>Hughes-Liu (Type 1)</td>
</tr>
<tr>
<td>Belytschko-Tsay (Type 2)</td>
</tr>
<tr>
<td>Belytschko-Leviathan (Type 8),</td>
</tr>
<tr>
<td>Belytschko-Wong-Chiang (Type 10),</td>
</tr>
<tr>
<td>Fast Hughes-Liu (Type 11)</td>
</tr>
</tbody>
</table>

3.3.1 Test Scenario 1

In Test Scenario 1, a single shell element was stretched laterally at a constant speed on both sides using prescribed nodal displacement, as shown in Figure 29. The
material was modeled as pure elastic (MAT_ELASTIC). In the baseline model, the shell element was deformable throughout the simulation. The cross-section force and internal energy were recorded to show the shell’s deformation.

Then, a D-R switch was performed on the model. The shell element was stretched as in the baseline, but it was switched to a rigid body between 10.5 ms and 14.5 ms. Comparisons of cross-section force for each element are plotted in Figure 30. It is clearly shown that at 10.5 ms when the shells were switched to rigid, all of the selected shell types presented no deformation and maintained their status throughout the element’s rigid stage. Compared to the beam element, the shell element had zero stress after being switched to rigid, while the beam element kept a constant value from the pre-rigid stage. After the shell was switched back to deformable at 14.5 ms, all of the shells could retrieve their pre-rigid status and behaved as normal as before. Thus, in Test Scenario 1, D-R switching did not affect the selected shell elements’ performance.

Figure 29. Illustration of Shell Element Baseline Model - Test Scenario 1
Cross-section Force Comparison

Internal Energy Comparison

Figure 30. Shell Element D2R Performance, Test Scenario 1
3.3.2 Test Scenario 2

Test Scenario 2 added rotational movement to the shell’s stretch after the elastic shell was stretched laterally between time 0 and 10 ms. Then the stretch of the shell was suspended, and the shell was rotated. At 15 ms, after rotating 90 degrees, the rotation was stopped and the shell started stretching in the vertical direction. An illustration of Test Scenario 2 is shown in Figure 31.

Figure 31. Illustration of Shell Element Baseline Model-Test Scenario-2

Then, D-R switching was conducted on the model. The shell element was stretched and rotated as in the baseline model, but it was switched to a rigid body between 10 ms and 15 ms. Cross-section force and internal energy of each shell element type are plotted against their baseline model results in Figure 32 through Figure 39.
Figure 32. HL(1) Shell Element D-R Performance
Figure 33. BT(2) Shell Element D-R Performance
Cross-Section Force Comparison

Internal Energy Comparison

Figure 34. BL(8) Shell Element D-R Performance
Figure 35. BWC(10) Shell Element D-R Performance
Figure 36. Fast HL(11) Shell Element D-R Performance
Cross-Section Force Comparison

Internal Energy Comparison

Figure 37. Full Integrate S/R HL(6) Shell Element D-R Performance
Cross-Section Force Comparison

Internal Energy Comparison

Figure 38. Full Integrate S/R Co HL(11) Shell Element D-R Performance
Cross-Section Force Comparison

Internal Energy Comparison

Figure 39. Full Integrate Shell(16) Shell Element D-R Performance
It is clearly shown that when the shells were switched back to deformable bodies at 15 ms, Types 1 and 6 shells could not retrieve the stored pre-rigid status. The force and energy developments after being switched back to deformable diverged from their initial deformable statuses. It was apparent that models with Type 1 and Type 6 shells were not compatible with D-R switching in Test Scenario 2. This is because Type 1 and Type 6 shells are derived in global coordinate. All the pre-rigid statuses were stored in global coordinates. After the model experiences rotational movement during its rigid period, the vector direction was already different from the pre-rigid stage, when the shell was about to switch back to deformable.

Belytschko-Tsay (Type 2) and S/R co-rotational Hughes-Liu (Type 7) shell elements are based on a combined co-rotational coordinate. The co-rotational formulation avoids the complexities of the nonlinear mechanics and improves the efficiency by embedding a coordinate system in the element. The mid-surface of the shell element, or reference surface, is defined by the location of the element’s four corner nodes. An embedded element coordinate system that deforms with the element is defined in terms of these nodal coordinates, as shown in Figure 40. Using the co-rotational coordinates, all of the pre-rigid status is locally stored when the shell is switched to rigid, and this stored status is always valid no matter how the shell’s location changes.
Figure 40. Construction of Co-Rotational Coordinate in Belytschko-Tsay Shell

Shell Type 16 in LS-Dyna is a fully-integrated shell with assumed strain interpolants used to alleviate locking and enhance in-plane bending behavior. It uses a local element coordinate system that rotates with the material to account for rigid body motion and automatically satisfies frame invariance of the constitutive relations. The local element coordinate system is similar to the one used for the Belytschko-Tsay element, where the first two basis vectors are tangent to the shell midsurface at the center of the element, and the third basis vector is in the normal direction to this surface and is initially coincident with the fiber vectors.

3.3.3 2-D Element Summary

Eight commonly used shell types were investigated, including five reduced-integrated shells and three fully-integrated shells. Results showed that, without rotational movement, all the selected shells can be switched back and forth between deformable and rigid bodies smoothly. However, if the direction of a shell was changed when the element is rigid, Type 1 and Type 6 shells could not retrieve their initial status after being switched back to deformable, while the other shells were still compatible with D-R switches. This was because the calculations of Type 1 and Type 6 shells are derived in
global coordinates. When D-R switches begin, the final deformable status of the shell is stored, which is recorded using global coordinates. If the shell experiences any rotation during its rigid stage, the stored status does not match the shell’s new position any more, and the shell will present inaccurate results when it is switched back to a deformable body. Meanwhile, all the other selected shells use local coordinates. The shell status is directly related to the shell itself instead of the global coordinates. Thus, even if there are some rotational movements, the shell’s pre-rigid status is always valid. From the investigation herein, models using Type 1 and Type 6 shells should not conduct D-R switches if they might have any rotational movements.

3.4 Solid (3-D) Element

Similar to the beam and shell models, solid elements were also tested in two scenarios: with and without rotation. Three commonly used solid elements are selected herein: Constant Stress Solid (Type 1), Fully-integrated S/R solid (Type 2); and Fully-integrated solid with nodal rotations (Type 3).

3.4.1 Test Scenario 1

In Test Scenario 1, a single solid element is stretched laterally at a constant speed on both side faces using prescribed nodal displacement, as shown in Figure 41. The material is modeled as pure elastic (MAT_ELASTIC). In the baseline model, the solid element is deformable throughout the simulation, while in the D-R model, the solid element was switched to rigid between 10.5 ms and 14.5 ms. The cross-section force and internal energy from both the baseline model and D-R model are recorded and compared in Figure 42 through Figure 44. It is clearly shown that, without rotation, all three solid
elements could be switched to a rigid form smoothly, and they could also be switched back to deformable without affecting their original performance.

Figure 41. Illustration of Solid Element Baseline Model - Test Scenario 1
Figure 42. Constant Stress Solid (Type 1) D-R Performance
Figure 43. Fully Integrated S/R Solid (Type 2) D-R Performance
Cross-Section Force Comparison

Internal Energy Comparison

Figure 44. Fully Integrated Solid with Nodal Rotations (Type 3) D-R Performance
3.4.2 Test Scenario 2

Test Scenario 2 added rotational movements to the cube’s stretch, the elastic cube was stretched laterally between 0 ms and 10.5 ms. Then the stretch of the cube was suspended, and the cube started rotating. At 15 ms, after rotating 90 degrees, the rotation was stopped, and the cube started stretching in a vertical direction. An illustration of Testing Scenario 2 is shown in Figure 45.

Figure 45. Illustration of Solid Element Baseline Model - Test Scenario 2

Next, the D-R switch was conducted on the model. The solid element was stretched and rotated as in the baseline model, but was switched to a rigid body between 10.5 and 14.5 ms. Cross-section force and internal energy of each shell element type are plotted against their baseline model’s results in Figure 46 through Figure 48. It is clearly shown that both Type 1 and Type 2 solid elements could fairly well regain their original deformable nature after being switched back from the rigid status, while Type 3 solid cannot be switched back to a deformable body after rotation. Thus, Type 3 solid element is not compatible with the D-R switch in Test Scenario 2.
Cross-Section Force Comparison

Internal Energy Comparison

Figure 46. Constant Stress Solid (Type 1) D-R Performance
Cross-Section Force Comparison

Internal Energy Comparison

Figure 47. Fully Integrated S/R solid (Type 2) D-R Performance
Figure 48. Fully Integrated Solid with Nodal Rations (Type 3) D2R Performance
3.5 Summary and Conclusions

Proper choice of element type is very critical for D-R switches. A series of investigations were performed to evaluate several commonly used elements in D-R switches. The investigations covered beam (1-D), shell (2-D), and solid (3-D) elements. Results proved that, without rotational movements, all of the selected elements can be switched between rigid and deformable statuses using D-R commands. However, if the component’s direction is changed, some elements will present inaccurate performance after being switched back to deformable bodies again, as shown in Table 4. Thus, beam elements, Type 1 and Type 6 shell elements, and Type 3 solid element are not recommended for D-R switches. Due to the time limitation, not all of the available elements were evaluated. The testing scenario provided herein can be used to evaluate any other element types in the future.
<table>
<thead>
<tr>
<th>Element Type</th>
<th>D-R Compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Rotation</td>
</tr>
<tr>
<td><strong>Beam Element (1-D)</strong></td>
<td></td>
</tr>
<tr>
<td>Hughes-Liu (Type 1)</td>
<td>Yes</td>
</tr>
<tr>
<td>Belytschko-Schwer (Type 2)</td>
<td>Yes</td>
</tr>
<tr>
<td>Truss (Type 3)</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Shell Element (2-D)</strong></td>
<td></td>
</tr>
<tr>
<td>Hughes-Liu (Type 1)</td>
<td>Yes</td>
</tr>
<tr>
<td>Belytschko-Tsay (Type 2)</td>
<td>Yes</td>
</tr>
<tr>
<td>Belytschko-Leviathan (Type 8)</td>
<td>Yes</td>
</tr>
<tr>
<td>Belytschko-Wong-Chiang (Type 10)</td>
<td>Yes</td>
</tr>
<tr>
<td>Fast Hughes-Liu (Type 11)</td>
<td>Yes</td>
</tr>
<tr>
<td>S/R Hughes-Liu (Type 6)</td>
<td>Yes</td>
</tr>
<tr>
<td>S/R co-rotational Hughes-Liu (Type 7)</td>
<td>Yes</td>
</tr>
<tr>
<td>Bathe-Dvokin Features in B-T (Type 16).</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Solid Element (3-D)</strong></td>
<td></td>
</tr>
<tr>
<td>Constant Stress Solid (Type 1)</td>
<td>Yes</td>
</tr>
<tr>
<td>Fully integrated S/R solid (Type 2)</td>
<td>Yes</td>
</tr>
<tr>
<td>Fully integrated solid with nodal rations (Type 3).</td>
<td>Yes</td>
</tr>
</tbody>
</table>
4 TREATMENT OF CONNECTIONS DURING D-R SWITCH

4.1 Introduction

A typical LS-Dyna model usually consists of multiple components. These components are assembled together using various connection modeling techniques. Potential issues might happen when D2R switching is applied on the system, because the connections of rigid bodies are considerably different from the connections of deformable bodies. Few connections are compatible with both deformable and rigid objects. For instance, the spot-weld connection cannot be used on any rigid body; while the extra-node-on-rigid-body connection requires that one component has to be deformable. These connections might fail when the deformable parts are switched to rigid. Thus, although each individual component within a system can be switched smoothly between the rigid and deformable statuses, the entire model might still fail if the connections are not properly handled.

Proper handling of connections during D2R should satisfy two requirements: The originally connected components are still connected together after switching to rigid bodies; and the original connections can be retrieved after the components are switched back to deformable bodies.

Several commonly used connections in LS-Dyna were investigated herein, including:

Merged-Nodes

Nodal-Rigid-Body (*CONSTRAINED_NODAL_RIGID_BODY)

Extra-Node-On-Rigid-Body (*CONSTRAINED_EXTRA_NODES)

Spot-Weld (*CONSTRAINED_SPOTWELD)
These connections above were implemented in the current pickup truck model used at MwRSF, as shown in Figure 49. Most of the connections are used to connect deformable body with deformable body, except that Extra-Node-On-Rigid-Body (*CONSTRINDED_EXTRA_NODES) connects rigid body with deformable body. It is noted that, for the merged-nodes connection, only one node is left for each duplicated location after the adjacent components are merged together. However, in order to be consistent with the other connections, separated nodal notations were still used in this study.

![Illustrations of Common Connections in LS-Dyna](image)

**Figure 49. Illustrations of Common Connections in LS-Dyna**

When switching a deformable body to a rigid body, the nodes on the deformable body used in a constraint definition such as * CONSTRAINED_SPOTWELD, * CONSTRANTED_NODAL_RIGID_BODY, etc, will prevent the formation of the new rigid body and cause instabilities during the simulation. This is due to the violation of the single constraint requirement on rigid bodies (10).
A series of switching scenarios were performed to investigate how the connections were treated during the D-R switch in LS-Dyna. The setup for the connection study during D2R switches is shown in Figure 50. Two identical shells were connected. Shell 1 was free of any constraints, and Shell 2 was accelerating in the positive X direction. Because of the connection, Shell 1 was moving with Shell 2 at the same speed. Both shells were modeled with deformable materials initially, except that shell 1 was initially rigid for the Extra-Nodes-On-Rigid-Body connection model. The baseline model was run without changing their materials. Nodal velocities were recorded to check the validity of connections between the shells. The results are shown in Figure 51.

![Figure 50. Baseline Model Set-Up](image)

**4.2 Partially (Single Element) D2R Switch**

In this scenario, Shell 1 was switched to a rigid body at 3 ms, while Shell 2 was maintained as deformable throughout the simulation, as shown in Figure 52. All of the connection types (except extra-node-on-rigid-body) were tested using this switching scenario, and the results are plotted in the form of velocity difference between the two shells, as shown in Figure 54.
It is shown that, for connections of Merged-Nodes and Nodal Rigid Body, the two shells still moved together as before when Shell 1 was switched to a rigid body. For the Spot-Weld connection, Shell 1 and Shell 2 moved at different speeds after Shell 1 was switched to rigid body at 3 ms. The velocity histories demonstrated that Merged-Nodes, Nodal Rigid Body, and Contact-Tied-Nodes-To-Surface connections were still valid, while Spot-Weld connection between the two shells failed when shell 1 was switched to rigid body but shell 2 was still deformable.

**Figure 51. Velocity Comparison in Baseline Run**
Figure 52. Switching Command—Single Component D2R

4.3 Partially (Single Shell) D2R and R2D Switches

Based on the previous section, further investigations were developed to see how the connections behaved when the R2D switch was performed later. After switching to a rigid body at 3 ms, Shell 1 was switched back to deformable at time 7 ms, as shown in Figure 53. Corresponding velocity difference histories are plotted in Figure 55.

Results showed that Merged Nodes Connection, Nodal Rigid Body, and Contact-Tied-Nodes-To-Surface connections were not affected after Shell 1 was switched back to deformable body. However, it was noticed that the Spot-Weld connection was recovered after Shell 1’s deformability was regained.
Figure 54. Velocity-Difference Comparison during Partial D2R Switch

Merged-Nodes

Nodal Rigid-Body Constraint

Spot Weld

Contact-Tied-Node-To-Surface
Figure 55. Velocity Comparison during D2R and R2D - Single Shell Switch
Therefore, when connected components are partially switched to rigid, Merged-Nodes Connection and Nodal Rigid Body connection could allow the connected component to be partially switched to a rigid body.

Spot Weld connection failed when one component was switched to rigid but the other one was still deformable. When that component was switched back to deformable, spot-weld connection was recovered.

4.4 Entire (Both Shells) D-R Switch without Master Body

As mentioned previously, LS-Dyna offers options of merging with a master body during D2R switching. This scenario was to switch the entire system (both shells) into rigid without using a master body. Both of the shells were set to switch to rigid bodies at 3 ms, as shown in Figure 56.

```
*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw paried
  1                 3
$ nrbf ncsf rwf dtmax d2r r2d
  2
$$
$ partID master
  1
  2
$$
Figure 56. Switching Command - Both Components D2R without Master Body

Without merging with a master body, a component is considered as either independent or master body itself (1). It turned out that switching both of the shell without a master body caused calculation errors for models using Merged-Nodes connection, Nodal Rigid Body, and Contact-Tied-Nodes-To-Surface connections. This was because the nodes that construct the connections between the two shells will be double defined as rigid bodies in this case.
However, for the spot-weld connection model, the simulation was accomplished without any calculation errors. The Cross-section forces of both shells are plotted in Figure 57. Results revealed that the spot weld failed when both of the shells were switched to rigid bodies, and the two shells were apart from each other.

**Figure 57. Velocity Difference History - Both Shells D2R Switch w/o Master Body**

Further study showed that without defining a master body, the spot-weld connection will be deactivated when both shells are switched to rigid bodies, but the connection was recovered after they switched back to deformable bodies, as shown in Figure 58.
4.5 Entire (Both Shells) D-R Switch with Master Body

In this case, both shells were switched to rigid bodies with one of them (shell 1) defined as the master body, and the other was merged to the master body, as shown in Figure 59.

```
*DEFORMABLE_TO_RIGID_AUTOMATIC
$   swset     code    time1    time2    time3    entno    relsw  paried
1                 3
$    nrbf     ncsf      rwf    dtmax      d2r     r2d
2
$$
$   partID    master
1          1
2          1
$
```

Figure 59. Switching Command - Both Components D2R with Master Body

Then both of the shells were switched back to deformable bodies at 7 ms after they became rigid bodies, as shown in Figure 60. Simulation results proved that all the
original connections were retrieved when the shells became deformable again, as shown in Figure 61.

*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw paried
  2               7
$ nrbf ncsf rfw dtmax d2r r2d
  2
$$
$ partID master
  1
  2
$$

**Figure 60. Switching Command - Both Components R2D with Master Body**

**Figure 61. Cross-Section Forces during D2R and R2D with Master Body**

4.6 Entire D2R Switch and Partial R2D Switch using Master Body

As shown in the section above, all of the components in a model are usually switched back to deformable at the same time. However, there might be some situations that the connected components are preferred to switch back to deformable bodies at different times.
Investigations were conducted in this section to show how the connections behave when the components were switched back to deformable bodies at different times. The switching scenarios was designed as both shells become rigid at time 3 ms, but only one was switched back to deformable at 7 ms, as shown in Figure 62.

Simulation results showed that both Merged-Nodes and Nodal-Rigid-Body connections could still hold the shells together after one was switched back to deformable earlier than the other, but the spot weld connection failed, as shown in Figure 65.

```
*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset  code  time1  time2  time3  entno  relsw  paried
  1                   3
$ nrbf  ncsf  rwf  dtmax  d2r  r2d
  2                    1

$ partID  master
  1   2   1

*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset  code  time1  time2  time3  entno  relsw  paried
  2                   7
$ nrbf  ncsf  rwf  dtmax  d2r  r2d
  1                    1

$ partID  master
  2
```

Figure 62. D2R and R2D Switching Command with Master Body

Figure 63. Velocity Difference History - Merged-Nodes Connection
4.7 Rigid-Body Irreversible Merge

In a LS-Dyna model, some components might be initially simplified as rigid bodies in order to improve the simulation efficiency. Like the deformable bodies, the
rigid components also need to be merged with the master body to keep their connections during D2R switches. According to the analysis above, after a component was switched to rigid and was merged with the master body, the R2D switch was necessary to separate the component from the master body, and to retrieve the original connections. In other words, the R2D switch is the only way to separate a switched component from the master body. However, because the rigid bodies are initially rigid, the R2D switch cannot be applied on them. Therefore, the initially rigid components cannot be separated again and will stay merged permanently once they are merged together for the D2R switch. In order to demonstrate this phenomenon, an example is shown in Figure 66. Shells 1, 2, and 3 were three individual shells, which were separate from each other. Shells 1 and 3 were initially rigid, while Shell 2 was initially deformable. Shell 1 was fixed at its C.G. location, while Shells 2 and 3 didn’t have any constraint. Thus, in the baseline model, Shell 2 and Shell 3 fell due to the gravity, while Shell 1 stayed at its original location because of the constraint, as shown in Figure 66.

Figure 66. Multi - Rigid System
Then all three shells were switched to rigid, with Shell 1 serving as the master body. Shell 2 and Shell 3 were merged with Shell 1; thus the three shells act as one piece of rigid body after switching to rigid. R2D switch was conducted afterwards, since Shell 3 was initially rigid, only Shell 2 was able to be switched back to deformable and be separated from the master body. Results proved that Shell 3 was still merged with Shell 1, as shown in Figure 67.

![Figure 67. Rigid Bodies are Permanently Merged after D2R](image)

To avoid the permanent merge, the initially rigid component has to be used as the master body. If more than one rigid body exists in a model, only one initially rigid component is allowed in the model, and all the other rigid components have to be remodeled as deformable bodies. Otherwise, the model can only perform one-way D2R switching and cannot be accurately switched back to deformable again.

### 4.8 Conclusion and Summary

As discussed in Chapter 3, whether an individual component’s D-R switch was accurate or not was mostly controlled by the proper element choice. But when the D-R switches were applied on a system, the switch might still fail even if every individual component in the system can be switched smoothly. This is because some connections
will cause instabilities during the simulation and prevent the formation of the new rigid body, due to the violation of the single constraint requirement on rigid bodies.

The method of keeping the original connections between each individual component is very critical to the D-R switch. In order to clarify the treatments of the connections during the D-R switch, investigations were conducted on four commonly used connections: Merged-Node, Nodal-Rigid-Body-Constraint, Spot-Weld, and Extra-Node-On-Rigid-Body. Different switching scenarios were tested, and the results were summarized in Table 5.

When the connected components are switched to rigid bodies, there are two options in LS-Dyna: with or without master body. Results in Table 5 show that, by defining a master body and merging the other components with the master body, all of the models could run without any calculation errors and the originally connected components were still connected together when they were switched to rigid bodies; Also, these connections can be immediately recovered when the components were turned back to deformable bodies. Therefore, defining a master body and merging all of the other components with the master body is recommended to keep the original connections during D2R switching. In this way, all of the connected components can stay together after being switched to rigid, and all of the original connections can be recovered after being switched back to deformable.

Extreme care needs to be taken if the components are not turned back to deformable at the same time. The spot-weld connection cannot be recovered for this case, even though the components are merged with a master body; while all other connections can allow the rigid bodies to be switched back to deformable at different times.
If a model has a rigid component initially, the rigid body has to be used as the master body for D2R switching; otherwise, it cannot be separated after merging with the master body and it will be permanently merged with the master body. This is because R2D is the only way to separate merged components, but the initially rigid component cannot be R2D switched. Meanwhile, in order to avoid the permanent merge, only one rigid component is allowed in a model for accurate D2R and R2D switches. If multiple rigid components exist in a model initially and the model is to have D2R/R2D switches, most of them have to be remodeled as deformable bodies.
<table>
<thead>
<tr>
<th>Switching Scenario</th>
<th>Connection Type</th>
<th>Simulation Accomplished</th>
<th>Connection Valid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Shell D2R switch at 3 ms</td>
<td>Merged-Node</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Nodal-Rigid-Body- Constraint</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Spot-Weld</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Both Shells D2R switch at 3 ms without Master body</td>
<td>Merged-Node</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Nodal-Rigid-Body- Constraint</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Spot-Weld</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Extra-Node-On-Rigid-Body</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td>Both Shells D2R switch at 3 ms and R2D at 7 ms without Master body</td>
<td>Merged-Node</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Nodal-Rigid-Body- Constraint</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Spot-Weld</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Extra-Node-On-Rigid-Body</td>
<td>No</td>
<td>NA</td>
</tr>
<tr>
<td>Both Shells D2R switch at 3 ms with Master body</td>
<td>Merged-Node</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Nodal-Rigid-Body- Constraint</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Spot-Weld</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Extra-Node-On-Rigid-Body</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Both Shells D2R switch at 3 ms with Master body and R2D switch at 7ms</td>
<td>Merged-Node</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Nodal-Rigid-Body- Constraint</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Spot-Weld</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Extra-Node-On-Rigid-Body</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Both Shells D2R switch at 3 ms with master body, but only one shell R2D switches at 7ms</td>
<td>Merged-Node</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Nodal-Rigid-Body- Constraint</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Spot-Weld</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
5 MASS AND INERTIA CHANGE IN DEFORMABLE AND RIGID SWITCH

5.1 Introduction

The mass and inertia of a deformable component might be modified by default in LS-Dyna when a D2R switch is applied, as shown in Example V of Chapter 2. The cause of the mass change during D2R has not been clarified in the literature, and little information is currently available to solve the mass change phenomenon. Since the mass change might affect the model’s behavior after a D2R switch, it is necessary to further understand this phenomenon. Investigations were conducted in this chapter to reveal the rules of mass change in D2R. It was found that the mass change of a component during D2R was caused by the connections that were attached to this component. And the amount of mass change was mainly controlled by the connection types. The effects of different connections on mass/inertia change were then summarized. Meanwhile, the investigations also found the mass change only occurred when a model was partially D2R switched. Instead, if all the components of a model were D2R switched, there was no mass changed observed in this model. In the end, solutions were provided to correct the mass and inertia errors in the D2R switch.

5.2 Mass Calculation of Rigid Body in LS-Dyna

In LS-Dyna, a component’s mass is calculated based on the nodes that construct the component (1 and 10). By default, LS-Dyna considers the connection nodes as a part of the connected rigid body, which will over-calculate the rigid body’s actual mass. Three simple models are presented in Figure 68 to show how the rigid body masses are calculated in LS-Dyna.
Case (a) in Figure 68 is a model consisting of two shells, with one being rigid and the other being deformable. Shell 1 is meshed by nodes #1, #2, #3, and #4, and Shell 2 is meshed by nodes #5, #6, #7, and #8. Each shell has the same weight of $m$, which is evenly distributed to its own 4 nodes. In other words, each node has a mass of 0.25 $m$. The two shells are connected by merging their overlapped nodes (#2 and #5, #3 and #8) together. However, when the model is processed in LS-Dyna, the actual rigid body mass is $1.5m$ instead of the desired $m$. And the deformable part is $0.5m$. This is because, by sharing the overlapped nodes, nodes #5 and #8 from Shell 2 are directly attached to Shell 1, and they are considered a composition of Shell 1 in LS-Dyna.

Case (b) in Figure 68 also includes one rigid shell and one deformable shell, except the two shells are connected using extra nodes on the rigid body. Thus, the actual mass of the rigid body includes its own original four-nodal mass of $m$ plus the extra mass from the nodes of shell 2 that are defined as extra nodes on the rigid body, which means part of the mass of Shell 2 is also accounted for in shell 1. The mass of the rigid shell is $1.5m$ in this case, and the deformable part is $0.5m$.

In Case (c), the two deformable shells in Figure 68 are connected by defining nodal rigid bodies between nodes #3 and #8 as well as between nodes #2 and #5. When
LS-Dyna processes this model, the deformable portion 1 only has the mass of nodes #1 and #4, and deformable portion 2 only has the mass of nodes #6 and #7, which are both 0.5 m. Meanwhile, nodes #2 and #5 form a rigid body with a mass of 0.5 m, and nodes #3 and #8 form another rigid body with a mass of 0.5 m as well. The masses for the two deformable part is 0.5 m each.

According to the rigid body mass calculation mechanism in LS-Dyna, a component’s mass might be changed after switching from deformable body to rigid body, and the change is related to the particular connection types that are originally attached to the deformable component.

5.3 Mass Change in Partially Switched Models

As previously mentioned in Chapter 4, Merged-Node Connection and Nodal Rigid body Connection allow a deformable component to keep its original connections without merging with the master body during D2R switch. Thus, a model using these two connection types can be partially switched without switching all of its components. Because the original connections still connect the newly formed rigid body, the connection nodes will contribute to the new rigid body’s mass and result in undesired mass/inertia change after D2R switch. Further investigations are conducted in this section into the mass changes when a LS-Dyna model is partially switched to rigid.

5.3.1 Mass Change Effect of Merged-Nodes Connection

When several deformable components are connected using merged nodes, the mass of the merged nodes will be double-calculated into the newly formed rigid body after the D2R switch. The effect of merged-node connection on the mass change during D2R was demonstrated herein through the use of a simple-model example. The baseline
model consists of two identical deformable shells, which were both free from all directional constraints and were connected by merging the overlapped nodes. The entire simulation lasts 10 ms. In order to demonstrate the changes of mass and inertia, the model was tested in translational and rotational movements respectively.

![Diagram of Merged-Nodes Translational Movement Model]

**Figure 69. Merged-Nodes Translational Movement Model**

### 5.3.1.1 Mass Change Effect in Translational Movement

An initial translational velocity was applied on the baseline model at time zero, and both of the shells are moving in the positive X-direction, as shown in Figure 69. The kinetic energy can be expressed as \( W = \frac{1}{2}m v^2 \). Since the velocity was constant throughout the simulation, the change of kinetic energies can indicate the mass change during the D2R switch.

In order to test the mass change in the D2R switch, shell 2 was switched to a rigid body between 3 ms and 7 ms.
Figure 70. Kinetic Energy History during D2R-Translational Movement

It is clearly shown in Figure 70 that the kinetic energy of shell 2 was increased during its rigid phase, while the kinetic energy of shell 1 was constant throughout the simulation. The change of the kinetic energy implied that extra mass was added to shell 2 when it was switched to a rigid body. The change of mass can also be proved directly by reading the d3hsp file, as shown in Table 6.

Table 6. Mass, C.G. and Inertia Change during D2R

<table>
<thead>
<tr>
<th></th>
<th>Shell 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformable Phase</td>
<td>Mass (mm)</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>Rigid Phase</td>
<td>1.125</td>
</tr>
</tbody>
</table>

According to the analysis in section 5.2, the mass change of shell 2 is resulted from the current mass calculation mechanism for rigid bodies in LS-Dyna. Figure 71
illustrates the mass change of shell 2 before and after the D2R switch. The left of Figure 71 represents the mass constitution of shell 2 before switching, which includes 4 nodes (#5, #6, #7, and #8). The right of Figure 71 represents shell 2 after being switched to rigid body, which includes 2 extra nodes (#2 and #3) from the merged boundary with shell 1. Thus, the mass of shell 2 was increased by half of its original mass. Correspondingly, the C.G. location of shell 2 was also shifted closer to the left. However, the kinetic energy of the entire the system was ironically constant throughout the simulation even with the increased kinetic energy of shell 2. It means, for translational movement, a partially switched system only causes mass error on the particular switched component, but does not affect the entire system’s performance.

![Original Shell 2 Mass Distribution](image1.png) ![Rigid Shell 2 Mass Distribution](image2.png)

**Figure 71. Illustration of Mass Calculation for Merged Nodes Connection**

### 5.3.1.2 Mass Change Effect in Rotational Movement

To investigate the inertia change after D2R, the model was then tested in a rotational movement. The baseline model was pinned at node #4, and the two shells rotate around node #4 due to an initial vertical velocity applied on shell 2, as shown in Figure 72. In a rotational movement, the kinetic energy can be expressed as $W=$
\( \frac{1}{2}I\omega^2 \). If the angular velocity \( \omega \) is constant, the change of the kinetic energy \( (W) \) reflects the change of the inertia \( (I) \).

Similar to the translational case, shell 2 was switched to a rigid body between 3 ms and 7 ms, while shell 1 was kept as deformable throughout the simulation.

Figure 72. Merged-Nodes Rotational Movement Model

As shown in Figure 73, shell 2’s mass was increased during its rigid period, which was also observed in the translational case. The entire system’s kinetic energy wasn’t changed when shell 2 was switched to rigid, but it was increased after shell 2 was switched back to a deformable body. At the same time, shell 1’s kinetic energy was also slightly changed when shell 2 was switched to a rigid body. It indicates that, for rotational movements, the entire model’s behavior is affected by the mass change when the model is partially switched to rigid body.
5.3.2 Mass Change Effect of Nodal-Rigid-Body Connection

Besides the merged-node connection, the nodal-rigid-body connection also allows a system to be partially switched to rigid body. To test its effect of mass change in a D2R switch, a simple baseline model is set up, which consists of two identical shells. The two shells were initially modeled with deformable material and are connected using nodal rigid body constraints between #2 and #5 as well as between #3 and #8, as shown in Figure 74. The entire simulation lasts 10 ms and shell 2 was switched to a rigid body between 3 ms and 7 ms, while shell 1 was deformable throughout.

5.3.2.1 Mass Change Effect in Translational Movement

The model is first tested with a translational movement. An initial translational velocity was applied on the model, and the two shells moved in the positive X-direction, as shown in Figure 74. Kinetic energy histories are plotted in Figure 75.
Figure 74. Nodal-Rigid-Body Translational Movement Model

It is shown that kinetic energy of shell 2 was increased when it was rigid, and no changes occurred on the kinetic energies of shell 1 or the entire system. The change of shell 2 kinetic energy is resulted from the increase of rigid body mass. Nodes #5 and #8 are originally part of the nodal rigid body connections. When shell 2 was switched to a rigid body, since the nodes #5 and #8 were on shell 2, the two nodal rigid bodies were by default considered by LS-Dyna as a part of the newly formed rigid body. Thus, the rigid shell 2 mass included masses from nodes #3, #2, #5, #6, #7, and #8, which was larger than its actual weight and results in the change of kinetic energy.
5.3.2.2 Mass Change Effect in Rotational Movement

The effect of the nodal-rigid-body connection on the mass change was then tested in a rotational system. The two-shell system was pinned at node #4 and rotated, as shown in Figure 76. Kinetic energies of the system and each shell are plotted in Figure 77. Similar to the translational case, shell 2 had increased energy when it was rigid. However, slightly increased kinetic energy was observed on shell 1 in the rotational model when shell 2 was rigid, and the entire kinetic energy was not affected when shell 2 was rigid, but was slightly increased after shell 2 was switched back to deformable.
Figure 76. Nodal -Rigid Body Rotational Movement Model

Figure 77. Kinetic Energy during D2R-Rotational Movement
5.4 Mass Change in Entirely Switched Model

It was proved in section 5.3 that when a model was partially switched to rigid, there was error in mass calculation, and the mass error might further affect the entire model’s behavior. In this section, investigations were conducted through the use of a series of simulations to find how the mass changed when all of the components of a component were D2R switched. Meanwhile, according to the analysis in Chapter 4, merging with a master rigid body was recommended to keep the original connections in D2R switches. Thus, a master rigid body was defined, and all the other components were merged with this master rigid body when all the components were D2R switched.

The baseline model consisted of two connected identical deformable shells. Both shells were switched to rigid bodies at time 3 ms, with shell 1 serving as the master body. Shell 2 was merged with the master body (shell 1) when it was switched to a rigid body. Then both of the two shells were switched back to deformable bodies at time 7 ms.

The D2R switch was tested in both translational and rotational movements, and they were tested with four different connections: merged-node connection, nodal-rigid body connection, extra-node on rigid body connection, and spot weld connection. The results are plotted in Figure 78 and Figure 79. It is shown that all the mass was transited to shell 1 when the two shells are switched to rigid bodies; while there was no mass change at the system level. This was because both the shells were merged together, and the master body (shell 1) represented the entire system during the rigid period. Thus, by defining a master body and merging its connected component, the entire model’s behavior was not affected by the D2R switch, which was observed in both translational and rotational movements.
Figure 78. Kinetic Energy Change during D2R - Translational Movement
Figure 79. Kinetic Energy Change during D2R - Rotational Movement
5.5 Mass Error Solution

As discussed previously, when a model is partially D2R switched in LS-Dyna, the mass of the switched component will be mistakenly increased by including the connection nodes into the new rigid body formation. The unrealistic mass change might affect the entire model’s simulation accuracy and may need to be fixed.

One way to overcome the mass change is through the use of *Deformable_To_Rigid_Inertia. Instead of calculating the mass and inertia from the attached meshes, *Deformable_To_Rigid_Inertia allows the users to manually define the new rigid body’s C.G. and inertia after D2R switching.

![Two-Shell System with Merged-Nodes Connection](image)

**Figure 80. Two-Shell System with Merged-Nodes Connection**

As previously shown, the original C.G. and inertia of shell 2 are changed after D2R if it was not merged with a master body. As shown in Figure 80, Shells 1 and 2 were connected with merged nodes and were moving at a constant velocity in the positive X direction. Shell 2 was switched at time zero and was switched back to deformable at 5 ms, and shell 1 was deformable throughout the simulation. Two runs were conducted to compare the D2R mass change with and without using *Deformable_To_Rigid_Inertia.
In Run 1, shell 2 was switched to a rigid body using *Deformable_To_Rigid, as shown in Figure 81. The kinetic energy is plotted in Figure 82. Due to the merged nodes, the mass of rigid shell 2 was larger than its original deformable mass.

```
*DEFORMABLE_TO_RIGID
$   pid   2
$
*DEFORMABLE_TO_RIGID_AUTOMATIC
$...>....1....>....2....>....3....>....4....>....5....>....6....>....7....>....8
$    swset     code     time1     time2     time3     entno     relsw
pared  2                   5
$   nrbf     ncsf     rwf     dtmax     d2r     r2d
$     partID     master
               2
$
```

Figure 81. D2R Input for Run 1

![Figure 82. Kinetic Energy of D2R without *Deformable_To_Rigid_Inertia](image-url)
In Run 2, shell 2 was switched to a rigid body using *Deformable_To_Rigid_Inertia, as shown in Figure 83. The C.G coordinates and the inertia of shell 2 were manually defined as the values that shell 2 originally had in its deformable status. The kinetic energy is plotted in Figure 84, and it was clearly shown that the issue of mass and energy change was fixed and the model’s behavior was not affected by the D2R switch.

```plaintext
*DEFORMABLE_TO_RIGID_INERTIA
$ pid 2
$ xc yc zc tm 7.5 2.5 0
$ ixx ixy iyy iyz izz 0.47e-3 0 0.47e-3 0 0.94e-3

*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw paried
$ nrbf ncsf rwf dtmax d2r r2d 1
$ partID master 2
$
```

Figure 83. D2R Input for Run 2 using *Deformable_To_Rigid_Inertia

![Material Summary](image)

Figure 84. Kinetic Energy of D2R using *Deformable_To_Rigid_Inertia
Therefore, implementing the command of *Deformable_To_Rigid_Inertia was proved to be an effective way to overcome the mass change caused by partially D2R switched in LS-Dyna models. However, there was a limitation of the application of this command. The command of *Deformable_To_Rigid_Inertia can only start switches at the beginning (Time 0) of a simulation, if a D2R switch is desired to be activated in the middle of a simulation, alternative ways other than *Deformalbe_To_Rigid_Inertia are necessary.

5.6 Conclusion

Due to the current mass calculation mechanism of rigid bodies in LS-Dyna, components might have undesired mass increase when they are switched to rigid bodies. The amount of mass change is controlled by the connection types that are originally attached to the switched components. Certain connections, such as Merged-Nodes connection and Nodal-Rigid-Body connection, allow components to be switched to rigid bodies without merging with a master body. Thus, the mass of all the connection nodes will be counted as part of the newly formed rigid bodies and increase the mass of the switched components.

A series of investigations proved, in a partially switched model, when a component was switched to rigid without merging with a master rigid body, it had inaccurate mass change when it was rigid. Depending on the system’s movement, the mass change might affect the entire system’s behavior and presented inaccurate simulation results. When a system only performed translational movement, the mass change was limited to that particular switched component; and it did not affect other components or the entire system’s behavior. However, if the system experienced any
rotational movements, all the components and the entire system’s behavior were affected by the D2R switch. Therefore, one should be very cautious in applying D2R in a partially switched LS-Dyna model.

The command of *Deformable_To_Rigid_Inertia can overcome the inaccurate mass change by manually overwriting the component’s C.G. location and inertia, which are usually calculated from the mesh nodes.

Meanwhile, investigations show the mass change occurs only when a system is partially switched to rigid. When a model’s components are all switched to rigid by merging with a master body, all the masses will be transferred to the master body. But the entire system’s mass is kept constant and its performance is not affected. Thus, in order to avoid inaccurate mass change, it is recommended to fully switch a model if possible and merge the switched components with a master rigid body when performing D2R switches.

However, for a large model with lots of nodes and elements, even if the model is only partially D2R switched, the mass difference may be insignificant since the mass of the connecting nodes may be minimal compared to the overall mass of each component.
6 TREATMENT OF BOUNDARY CONDITIONS DURING D2R/R2D

6.1 Introduction

Boundary conditions (B.C.) of a deformable object are applied on the mesh nodes, while descriptions of a rigid body are mainly based on its C.G. Therefore, when a deformable body is switched to a rigid body, besides the transition of the material’s properties and deformation from the deformable stage to the rigid stage, there is also a transition of boundary conditions from the nodes to the C.G. of the rigid body. The handling of boundary condition transition is very critical to D2R switches. However, the manner in which LS-Dyna handles the B.C. during D2R switching has not yet been clearly stated so far. In this chapter, the performances of three commonly used boundary conditions were investigated in combination with D2R/R2D switches: Nodal Constraints, Initial Velocities, and Prescribed Motions.

6.2 Nodal Constraint

Nodal constraints are not recommended for use with a rigid body (1). Otherwise, unexpected behaviors might happen. If a deformable object originally bears nodal constraints, the constraints will be deactivated by LS-Dyna when the object is switched to rigid body. These deactivated nodal constraints can also be recovered immediately when the object is switched back to a deformable body.

A simple model is shown in Figure 85 to demonstrate the behavior of Nodal Constraint during D2R and R2D switches. The model consists of two shell elements, which are connected by merging overlapped nodes. Both shells were deformable; Shell 1 was fixed by nodal constraints on nodes #1 and #4, while shell 2 was stretched on nodes
#5 and #6. In the baseline run, the shells were stretched for 10 ms and the trajectories of node 1 and node 4 are plotted in the left of Figure 86.

![Diagram of nodes and shells](image)

**Figure 85. Illustration of Nodal-Constraint Model**

Then, in a D2R switching run, shell 1 was switched to rigid at 3 ms and was switched back to deformable at 7 ms. Trajectories of nodes #1 and #4 are plotted in the right of Figure 86. It was clearly shown that the nodal constraints failed when shell 1 was rigid, but they were immediately retrieved when shell 1 was switched back to a deformable body.

However, the treatments of the single point constraints during D2R switching are fairly unstable and inconsistent in LS-Dyna. More simulations show that the results could vary by element type, the choice of master body, movement type, constrained freedoms, and even computer hardware. Thus, single point constraint is not recommended with D2R switches and should be removed or be replaced if it is possible.
Figure 86. Deactivation and Reactivation of Nodal Constraints with D2R
6.3 Initial Velocity

The initial velocity only defines the object’s motion at time zero, and the initial velocities are originally applied on the mesh nodes. When the object is switched to a rigid body, the current velocity is saved, and LS-Dyna calculates the new rigid body’s C.G. motion based the saved nodal velocity field. Then, the translational and rotational velocity of the nodal points are computed and reset to the new values. In this section, both translational and rotational motions defined by initial velocity are tested working with D2R switches.

6.3.1 Translational Movement

Figure 87 is the simple model set up to demonstrate the D2R effect on initial translational velocity. The model was a shell element that was free from any constraints, and was moving in the positive X-direction at a speed of 1 m/s. The shell was initially deformable, but was switched to rigid at 3 ms. Then the shell was switched back to deformable at 7 ms. The nodal velocity and acceleration are plotted in Figure 88. It is shown that the object’s translational movement was not affected after switching to a rigid body and switching back to deformable.

![Figure 87. Shell Movement under Initial Translational Velocity](image-url)
6.3.2 Rotational Movement

Figure 89 is the setup to demonstrate the D2R effect on the initial rotational motion. A shell was constraint-free and was rotating around its C.G. location. Rotation of
the shell was defined by initial velocity. The shell was initially deformable and was switched to rigid at 3 ms. Then the shell was switched back to deformable at 7 ms. Velocities and accelerations of each node are plotted in Figure 90.

![Figure 89. Shell Movement under Initial Rotational Velocity](image)

As shown in the left of Figure 91, that shell’s rotational velocity was the same before and after being switched to a rigid body. It was noticed that there was a slight disturbance when the object was switched to a rigid body, as shown in Figure 91. This disturbance can also be visually noticed in the simulation. However, the slight disturbance in rotational acceleration is insignificant as far as the rotational velocity is concerned.
6.4 Prescribed Motion

Prescribed motions define object motions at every single time step throughout the simulation instead of a uniform initial value. This is different than the initial velocity. Extreme care must be used when prescribing motion of a rigid body node. Nodes which belong to rigid bodies must have motion consistent with the translational and rotational...
velocities of the center of gravity of the rigid body. During initialization, the rigid body translational and rotational rigid body momenta are computed based on the prescribed nodal velocity field. From this rigid body momentum, the translational and rotational velocity of the nodal points are computed and reset to the new values. These new values may or may not be same as the values prescribed for the nodes that make up the rigid body. Sometimes this occurs in single precision due to the numerical round-off.

In LS-Dyna, prescribed motion is handled similarly to the nodal constraints (10). To avoid the instabilities during D2R, the prescribed motions on nodes are automatically deactivated when the object is switched to rigid body. This mechanism is similar to the treatment of nodal constraints during D2R switching. Meanwhile, the current motion status is saved simultaneously when D2R switching occurs. Then, the motion of the C.G. is calculated based on the saved motions, and all the nodal values are reset to a new value, which is similar to the handling of initial velocity during D2R.

Figure 91. Shell Accelerates in X Direction

A simple model was set up to demonstrate the handling of prescribed motion in LS-Dyna, as shown in Figure 91. A shell accelerated in the positive X-direction driven by
prescribed motions. Two runs were compared. In the baseline run, the shell was
deformable throughout the simulation; while in the D2R run, the shell was switched to a
rigid body between 3 ms and 7 ms. Velocity and acceleration of each run are plotted in
Figure 92 and Figure 93. This clearly showed that the prescribed accelerations failed
when the object was switched to rigid; but the velocity status before the rigid stage was
maintained during the rigid stage. After the shell’s deformable status was retrieved, the
prescribed motion was automatically re-activated again.

Then, similar to the initial velocity, both translational and rotational initial
motions defined by prescribed motions were also tested working with D2R switches, and
the results are plotted in Figure 94 and Figure 95. It is shown that the prescribed
translational motion could be smoothly transitioned when the object was switched to
rigid, while the transition of rotational prescribed motion was not stable.

Figure 92. Velocity Comparison of Prescribed-Motion Models
Figure 93. Acceleration Comparison of Prescribed-Motion Models

Figure 94. Acceleration and Velocity during D2R for Translational Prescribed Motion
Figure 95. Acceleration and Velocity during D2R for Rotational Prescribed Motion

6.5 Shift of Rotation Center during D2R

After an object is switched to a rigid body, the rotation center is by default considered as the C.G. location. Thus, if an object does not rotate around its C.G.
originally, its rotation center will be shifted from the original spot to its C.G. center, and the motion of the object will have unexpected errors.

A model is shown in Figure 96 to demonstrate the shift of rotational center after D2R. The shell is originally rotated around its upper left corner (Node #2). In the baseline model, the shell was deformable, and the trajectories of each of the nodes are plotted in Figure 97.

![Figure 96. D2R Affect on Initial Rotational Motion](image)

![Figure 97. Node Trajectories of Baseline Rotational Model](image)
Then, the shell was switched to rigid in the middle of the simulation, and the corresponding trajectories of nodes are plotted in Figure 98. It was clearly shown that the object movement was disturbed by the D2R switch. This was because the shell started rotating around its C.G. point instead of the original corner after being switched to a rigid body.

Figure 98. Node Trajectories of D2R Rotational Model

In order to avoid the shift of the rotation center during D2R and keep the original object movement, the command *DEFORMABLE_TO_RIGID_INERTIA should be applied. It allows the users to manually define the new rigid body’s C.G location. Thus, the rotation will be the same as before the D2R, if the user defines the new C.G. at the original rotation center. For instance, in the model shown above, its original rotating center was at Node #2, whose coordinate was (0, 5). However, the new C.G. was actually at (2.5, 2.5). To keep the original rotation after D2R, node #2 had to be defined at the
C.G. for the new rigid body, as shown in Figure 99. Nodal trajectories after implementing *DEFORMABLE_TO_RIGID_INERTIA are shown in Figure 100.

*DEFORMABLE_TO_RIGID_INERTIA

$\begin{align*}
\text{pid} & \quad \text{id} \\
1 & \\
\text{xc} & \quad \text{yc} & \quad \text{zc} \\
0 & \quad 5
\end{align*}$

$\$

Figure 99. Overwritten C.G. for D2R Rigid Body

Figure 100. Node Trajectories using *DEFORMABLE_TO_RIGID_INERTIA

6.6 Summary and Conclusion

A model’s motion is strongly influenced by its boundary conditions. Since some boundary conditions are not compatible with both deformable and rigid bodies, when a deformable object is switched to a rigid body, potential issues might occur.
Understanding how the boundary conditions are treated in LS_Dyna is very critical to assure the accuracy of D2R and R2D switches.

Investigations showed that nodal constraints on deformable bodies were deactivated by default when D2R switching occurred, and they were re-activated when the model’s deformability was recovered. However, the treatment of nodal constraints during D2R switches was found to be unstable in LS-Dyna. Therefore, the nodal constraints should be avoided if a D2R switch is to be conducted.

Initial velocity and prescribed motion are commonly used in LS-Dyna to describe an object’s motion. Initial velocity imposes motions on the object only at time 0, while prescribed motion acts on the objects throughout the simulation. It was found out that, for initial velocity, LS-Dyna calculated the C.G. motion of a new rigid body based on the nodal velocity field when D2R switching occurred. Then all the nodal velocities were reset to this new value; prescribed motions were deactivated when an object was switched to a rigid body, but the nodal velocity field at the time was saved. Then, the new rigid body’s motion was calculated based on the saved velocity field and all the nodes are reset to the new calculated values.

It was also found that the treatment of translational and rotational motions were different in D-R switches. For both the initial velocity and the prescribed motions, the translational motions could be smoothly transferred from the deformable stage to the rigid stage, while the transitions of the rotational movements were slightly affected when D2R occurs.

The entire handling process of boundary conditions during D2R and R2D is illustrated in Figure 101.
Also, extreme care must be used if a rotation is not originally around the C.G. location. In this case, the C.G. location of the new rigid body has to be manually overwritten using *Deformable_To_Rigid_Inertia to keep the original rotation. Otherwise, the rotational axis will be shifted to the actual C.G. location by default, resulting in unexpected movement of the switched model.
Figure 101. Illustration of Boundary Condition Handling during D2R/R2D Switches
7 CHOICE OF MASTER BODY IN DEFORMABLE AND RIGID SWITCH

7.1 Introduction

As previously discussed, for D2R switches, it is recommended to define a master rigid body and merge the other components with the master body to keep the original connections in the model. A model usually consists of multiple components, and all of these components interact with each other through different connections. Thus, there could be multiple options to pick a master body for a system D2R switch. Meanwhile, since each component might have different boundary conditions and is placed at different locations in a system, it is very likely that different choices of master body could result in different behaviors of the entire system. Investigations were performed in this chapter to provide guidelines for choosing the proper master rigid body for the D2R switch.

7.2 Chain Rule

In a multi-component system, some components are directly connected together, and others are not directly connected. To keep their original connections, all of the initially connected components should be merged together during the D2R switch with one of them serving as the master body. Thus, all of the directly connected components can be considered as a sub-system in the system, and each sub-system needs a master body to merge the other components for the D2R switch. In this way, a system could have several master bodies when D2R is conducted.

Figure 102 is an illustration of a multi-component system: System A, consisting of three components: 1, 2, and 3. Components 2 and 3 were directly connected with 1 and 2 respectively. Thus, 2 and 3, 1 and 2 could be considered as individual sub-systems, as shown in Figure 102. When a D2R switch was performed, 3 and 2 were merged together using 2 as the master body; 2 and 1 were merged together with 1 being the master body, as shown in Figure 103. In this way, 2
individual master bodies were defined, and the components were still connected after switching to rigid bodies.

Figure 102. Illustration of a Multi-Connection System

```
*DEFORMABLE_TO_RIGID
$ partID  master
  1
*DEFORMABLE_TO_RIGID
$ partID  master
  2   1
*DEFORMABLE_TO_RIGID
$ partID  master
  3   2
```

Figure 103. Master Body Definition-Option-1

However, it turns out, instead of using 2 master bodies, there is no difference if component 1 is picked as the only master body for the entire system and all the other components are merged with it for D2R switching, though component 3 is not directly connected to component 1 originally, as shown in Figure 104.

```
*DEFORMABLE_TO_RIGID
$ partID  master
  1
*DEFORMABLE_TO_RIGID
$ partID  master
  2   1
*DEFORMABLE_TO_RIGID
$ partID  master
  3   1
```

Figure 104. Master Body Definition-Option-2
This mechanism is very similar to a chain structure. The typical chain structure consists of multiple rings, and each ring can be considered as an individual component in the chain system, as shown in Figure 105. Most of the rings are not directly connected to each other, but through other rings. To move the entire chain, one only needs to move one ring, and all the other rings will move with this ring, though they are not directly connected to this ring. For convenience, the phenomenon observed in the D2R switch is referred as the Chain Rule. That is, whether or not the components are originally directly connected, they can be merged together with the same master body during a D2R switch. So, only one master body is needed for the entire system regardless of how many components are in the system and how the components are connected to each other.

![Figure 105. Illustration of a Chain Structure](image)

A simple model was conducted to further demonstrate the Chain Rule. A multi-component-multi-connection system is shown in Figure 106. Three shells were connected using 2 different connections: shell 1 and shell 2 are connected using merged nodes, and shell 2 and shell 3 were connected using nodal-rigid body Constraints. Meanwhile, shell 1 was constrained at its left side, and shell 3 were stretched outwards after 8 ms. The entire simulation ran for 10 ms. Cross-Section forces of each shell were recorded. Three runs: Baseline Run, D2R Run 1, and D2R Run 2 were conducted to prove the chain rule.
In the baseline run, all of the shells were deformable throughout the simulation, and the Cross-Section forces are plotted at the top of Figure 107.

In D2R Run 1, all of the three shells were switched to rigid at 3 ms. Shell 1 and shell 2 were defined as master bodies and merged with shell 2 and shell 3, respectively. Then, all of the shells were switched back to deformable at 7 ms, and the stretching started at 8 ms. The cross-section forces showed that the D2R switch did affect the system’s behavior, and all of the original connections could be accurately retrieved after D2R and R2D switches.

In D2R Run 2, all of the three shells were switched to rigid at 3 ms, but only shell 1 was defined as a master body, and both shell 2 and shell 3 were merged with shell 1. Then, all of the shells were switched back to deformable at 7 ms. Although shell 3 was not directly connected with shell 1 originally, the cross-section forces showed that the D2R switch using only one master body did not affect the system’s behavior, and all of the original connections could be accurately retrieved later.

### 7.3 Boundary Condition Effect on Master Body Choice

In a multi-component system, each component might bear different boundary conditions, and every component could possibly be used as the master body for D2R switching. It is not known yet whether the boundary condition on the master-body-to-be affect all members of the merged set during D2R or not.
Figure 107. Cross-Section Forces of Different Master-Body Choices
7.3.1 Models without Initial Rigid Bodies

An example is shown in Figure 108 to demonstrate the handling of boundary condition and master body choice during D2R switching. Shell 1 and Shell 2 were two identical deformable shells, but had different boundary conditions. Both Shell 1 and Shell 2 were moving in opposite directions at speeds of 0.2 m/s and 0.1 m/s, respectively. Then, both of the shells were switched to rigid at 5 ms. To keep the original connections between shells during the rigid period, one shell needed to be defined as the master rigid body, and the other was to be merged with the master body. Two runs were conducted to compare the difference between choices for the master body: Run 1 used shell 1 as the master body and merged shell 2 into shell 1, as shown in Figure 109. Run 2 used shell 2 as the master body and merged shell 1 into shell 2, as shown in Figure 110. The velocity changes are plotted in Figure 111. Both runs showed identical results, though Shell 1 and Shell 2 have different original boundary conditions. It proved that there is no difference between the two master body choices.

For a system containing no initially rigid bodies, it turns out that the master body does not control the system’s boundary condition during the D2R switch. The boundary condition of the master body does not apply on the other merged components. When the D2R switch is applied, all of the boundary conditions are treated together as a group as if they were applied on one piece of object, and the new rigid body’s movement is a result of the combination of all the individual boundary conditions. Therefore, any component in a system can be used as the master body. All prescribed motions or constraints are deactivated when the D2R switch occurs and every nodal movement is saved at the D2R switching moment. Then, the newly formed rigid body’s motion is recalculated based on the saved nodal motion field. All the nodal values are reset to the new value derived from the movement of the rigid body C.G.
In this case, nodes #1, 2, 3, and 4 had a velocity of -0.2 m/s when the D2R switch happened at 5 ms, while nodes #5, 6, 7, and 8 had a velocity of 0.1 m/s. The motion of the new merged rigid body’s C.G. was calculated as -0.1 m/s based on the saved nodal motion field. Then all the nodes were reset to this new velocity, as shown in Figure 111.

![Figure 108. Illustration of Multi-Boundary-Conditions System](image)

**Figure 108. Illustration of Multi-Boundary-Conditions System**

```plaintext
*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw pared
 1                 5
$ nrbf ncsf rwf dtmax d2r r2d
 2
$
$ partID master
 1 2 1
$
```

**Figure 109. D2R Switch of Run 1**

```plaintext
*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw pared
 1                 5
$ nrbf ncsf rwf dtmax d2r r2d
 2
$
```

**Figure 110. D2R Switch of Run 2**
Thus, for a model without initially rigid bodies, the choice of master body is irrelevant to boundary-condition. In other words, any components can be used as the master body for a system without initial rigid bodies, though they have different boundary conditions.
7.3.2 Models with Initial Rigid Bodies

Since initially rigid components cannot be included in the R2D switch, the components initially modeled with rigid materials will stay merged with the master body. Thus, the initially rigid component has to be used as the master body, and only one initially rigid component is allowed in a model to avoid the permanent merging.

If a model has more than one initially rigid component, the choice of a proper master body from these rigid components is mainly determined by the constraints/boundary conditions on the rigid components. It was found that the original constraints/boundary conditions on the initially rigid body were applied to the entire new rigid body after D2R switching, if the initially rigid body was used as the master body.

For convenience, the boundary condition that controls the entire system’s motion is herein referred to as *Critical Boundary Conditions*. If multiple rigid components exist in a model and they bear different boundary conditions/constraints, the one that owns that critical boundary condition/constraint has to be used as the master body, and all the other rigid components need to be remodeled as deformable.

An example of a multi-rigid model is shown in Figure 112. The model consisted of three shells. Shell 1 and Shell 3 were rigid bodies initially, but had different boundary conditions: Shell 1 was constrained at its C.G., while shell 3 was totally free from any constraints. To avoid the permanent merge and make the model two-way switchable, either Shell 1 or Shell 3 needed to be revised as deformable and the other stayed as rigid and served as the master body.
Two runs were performed to demonstrate the differences of master body choices. Run 1 used shell 1 as the master body, and Run 2 picked shell 3 as the master body. Results showed that the entire model stayed at its original location after switching to rigid in Run 1, while, in Run 2, the model fell due to gravity. This was because the original constraints of shell 1 were applied to the entire model after other components were merged with shell 1 in Run 1. Meanwhile, in Run 2, since shell 3 was initially free of constraint, no constraint was applied to the entire model when shell 3 was the master body.

Figure 113. Shell 1’s Constraint Applied on all the Merged Components
Figure 114. Shell 3’s Constraints Applied on all the Merged Components

In this case, since shell 1’s boundary condition controlled the entire system’s movement. Shell 1 was recommended to be the master body. Thus, for models with initially rigid bodies, the choice of master body was determined by the Critical Boundary Conditions.

7.4 Conclusion and Summary

A system usually consists of multiple components. The choice of a proper master body is very critical to conduct an accurate D2R switch. Some conclusions are reached through the investigations in this chapter.

The Chain Rule demonstrated that only one master body was needed for a D2R switch, and all of the other components could merge with this master body, regardless of how many components are in the system and how they were originally connected to each other. Also, all of the original constraints and connections could be retrieved when the system was switched back to deformable.

It was proven that any component could be used as the master body if a model did not have any rigid bodies initially. No matter how different their original boundary conditions were, the choice of master body did not affect the entire system’s behavior during D2R. The final
motion of the entire new rigid system was determined by the combination of all the components’ boundary conditions. In other words, boundary conditions during D2R were handled at the system level instead of each individual component’s level.

However, for a model that initially had rigid bodies, since the constraints/boundary conditions of the master body would be applied on the entire set of merged components, the rigid body that bore the critical boundary conditions had to be used as the master body.
8 GUIDELINES FOR IMPLEMENTING DEFORMABLE AND RIGID SWITCHES

8.1 Key Factors for D-R Switches

Through the simple-model investigations presented in the previous chapters, several key factors for utilizing the D-R switch were identified. They are: (1) the choice of element; (2) inter-component connections; (3) boundary conditions; and (4) the choice of master body. A model’s accuracy and reliability during the D-R switch are mainly determined by the treatment of these aspects.

8.1.1 The Choice of Element

Certain element types were found to be incompatible with the D-R switches. Investigations showed that the 1-D elements presented instabilities when the R2D switch was implemented. For 2-D elements, the elements that were derived on the global coordinates could not correctly retrieve their original deformable statuses when the R2D switch was implemented. For 3-D elements, the Type 3 solid element presented calculation errors when the R2D switch occurred. Several recommended element types are listed in Table 7.

Table 7. Recommended Elements for D-R Switches

<table>
<thead>
<tr>
<th>1-D Elements (Beams)</th>
<th>2-D Elements (Shells)</th>
<th>3-D Elements (Soilds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Belytschko-Tsay (Type 2) Belytschko-Leviathan (Type 8) Belytschko-Wong-Chiang (Type 10) Fast Hughes-Liu (Type 11) S/R Co-Rotational Hughes-Liu (Type 7) Bathe-Dvokin Features in B-T (Type 16).</td>
<td>Constant Stress Solid (Type 1), Fully-Integrated S/R solid (Type 2)</td>
</tr>
</tbody>
</table>

8.1.2 Inter-Component Connections

When the deformable components were switched to rigid, the original connections between the deformable components would potentially fail and cause calculation errors due to
their incompatibilities with the rigid material. In order to keep the components connected after being switched to rigid bodies, it is recommended that a master body be defined during the D-R switch and that all of the switched components be merged with the master rigid body. In this way, all of the original connections can also be immediately recovered after the rigid components are switched back to the deformable status.

However, the Merged-Node Connection can connect a rigid body with a deformable body. Thus, the components that are connected with this connection can be partially switched to rigid without merging them together.

Meanwhile, the connections can cause an unrealistic mass increase during the D2R switch. It occurs because part of the connection mass is included in the new-rigid body’s mass. The amount of mass increase depends on the particular connection definitions. If the mass increase is not negligible, it needs to be fixed. One of the solutions is to manually define the new rigid body’s mass, C.G., and inertia through the use of the command *DEFORMABLE_TO_RIGID_INERTIA. Nevertheless, it was noticed that the mass increase only occurred when the components were partially switched to rigid. If all of the components were switched to rigid and merged with the master body, there was no mass change for the entire model.

8.1.3 Boundary Conditions

Boundary conditions control a component’s movement. Boundary conditions of the deformable body are applied on its nodes, while the boundary conditions of a rigid body are defined on its C.G. The transition of the boundary conditions between the deformable body’s nodes to the new rigid body’s C.G. during the D-R switch was not previously clarified.
Simple-model investigations found that the single point constraints are automatically deactivated when the D2R switch occurs. The constraints were immediately recovered when the components were switched back to deformable body. However, the treatment of the single point constraint was found to be unstable in LS-Dyna. Therefore, it is recommended to remove or replace the single point constraint with other proper constraint techniques for the D-R switch.

If a component’s motion is defined by the initial velocity, the motion will not be affected by the D-R switches. LS-Dyna saves all of the nodal velocities when the component is switched to rigid, and the new rigid body’s C.G. movement is calculated based on the saved nodal velocity field. In this way, the motions defined on the nodes are transferred to the new rigid body’s C.G. The transfer of translational motion is seamless. The transition of the rotational motion shows a slight disturbance when D2R occurs, although the rotational velocity is not affected after switching.

When a motion is given by the prescribed motion, all of the current nodal motions are saved at the very moment when the D2R switch occurs. At the same time, the prescribed motion is deactivated. The C.G. motion of the new rigid body is then calculated based on the saved nodal motions. When the component is switched back to deformable, all of the nodes recover their motion status before switching to rigid, and the prescribed motion is reactivated again.

In general, LS-Dyna saves all of the nodal motions at the instant when the component is switched to rigid. Meanwhile, LS-Dyna deactivated all of the constraints and prescribed motions when the component is rigid. The C.G. motion of the new rigid body is calculated based on the saved nodal motions. When the component is switched back to a deformable body, all of the nodal motions before the D2R switch are recovered. At the same time, all of the constraints and prescribed motions are reapplied on the nodes again.
8.1.4 Master Body Choice

The use of a master body is always recommended during D-R switches in order to avoid the potential issues caused by the treatment of connections, such as failure of connection and mass change. No guidelines for choosing the master body are currently available. The choice of master body’s effect on a model’s behavior was not yet clarified.

Investigations in this study proved that only one master body is needed for a multi-component model, and all of the components can be directly merged with this master body, regardless if they are originally directly connected or not. This rule was referred as the “Chain Rule.”

If there is no initial rigid body in the model, any component can be chosen as the master body, regardless of their boundary conditions. However, if the model has an initial rigid body, the initial rigid body has to be used as the master body in order to avoid the permanent merge of the rigid bodies after the D2R switch. If there is more than one initial rigid body available in the model, the choice of the master body is determined by the rigid body’s boundary conditions. Because the boundary condition of the master rigid body is applied to all of the merged components, the initial rigid body that bears the critical boundary condition has to serve as the master body. In addition, the rest of initial rigid bodies need to be remodeled as deformable bodies if the permanent merge is not negligible.

8.2 Procedure of Implementing D-R Switch

Based on the findings from the simple model investigations, a procedure for implementing D-R switches on any LS-Dyna models was developed, as shown in Figure 115.
Switch All of the Components

No

Yes

Check whether the connections between the to-be-switched components and the surrounding deformable components are merged-nodes connections or nodal-rigid bodies.

Check if there are any components connected using * Contact-Tied-Nodes-To-Surface

Yes

No

Modify all of these connections to merged-nodes connections or nodal-rigid bodies

At least one of the connected components needs to be excluded from the to-be-switched group

Check whether any of the to-be-switched components are modeled with 1-D elements

Yes

No

Exclude the 1-D-element components from the to-be-switched group

Check whether any of the to-be-switched components are modeled with Type 1 Shell, Type 6 Shell, or Type 3 Solid elements

Yes

No

Modified all of the corresponding components using proper 2-D or 3-D elements

Check whether there are single-point constraints on the to-be-switched components

Continued on the next page

Figure 114. Proposed Procedure of Implementing the D-R Switch
No

Check whether there are initial rigid bodies in the to-be-switched components

No

Pick any component as the master body

Yes

More than one initial rigid body

Yes

Use the only initial rigid body as the master body

No

Use the rigid body that bears the critical boundary condition as the master body, and remodel the rest of rigid bodies to deformable bodies

Perform D-R switches and merge all the switched components with the master body

Evaluate the results and ensure the D-R switch did not affect the model’s behavior

Figure 115. Proposed Procedure of Implementing the D-R Switch (Continued)
8.3 Examples of the Application of D-R Switches

After summarizing the proposed procedure for applying the D-R switches. A couple of examples will be shown in the following chapters to prove the proposed D-R switching procedure and to demonstrate the improvement of the simulation’s efficiency through the use of the D-R switches.
9 APPLICATION OF D-R SWITCH ON CABLE STRUCTURE MODEL

9.1 Introduction

Cable guardrail systems have been widely used along roadsides and medians to prevent errant vehicles from impacting hazardous objects, as shown in Figure 116. A lot of research has been conducted to develop various new types of cable barrier systems. In order to reduce the financial and time cost, computer simulations were involved in the research and design process to model the cable structures (14). A preliminary cable model has been developed, and this cable is able to present satisfactory redirecting performance during the vehicle and cable impact.

![Figure 116. Median Cable Guardrail System](image)

However, the cable model showed insufficient bending stiffness. A large-scale cable model with a length of 186-m was presented herein to show the cable’s inaccurate shape under gravity. The cable was only pinned at both of the ends, and no post was modeled. A pretension
of 40 kN was applied to the beam element in the middle. Due to the lack of bending stiffness, the cable gradually sagged under gravity, and the stabilized shape is shown in Figure 117. The maximum vertical deflection of the cable reached as high as 5 m. Meanwhile, because the cable was modeled with a deformable material, it took an extremely long time for the deformable cable to stabilize, especially for the large-scale structures. For the 186-m cable shown in Figure 117, the stabilization of the cable model takes 1888 seconds (0 hours 31 minutes 28 seconds) using 4 CPUs on the Prairiefire cluster computer system at the University of Nebraska-Lincoln.

The sagging cable is difficult to use in modeling the high-tension cable barrier with large post spacing, whose cables are fairly straight in real life. In order to fix the cable’s unrealistic sag, the D-R switch was implemented into the cable model. The idea is to switch the cable to a rigid body at time zero and then switch it back to a deformable body right before the vehicular impact occurs. In this way, the cable can be kept straight without sagging. Meanwhile, by switching the deformable cable to rigid, the simulation time could be significantly reduced.
9.2 Proper D2R Switching Analysis

For convenience, investigations of proper D2R/R2D switches were first conducted on a simplified High-Tension-Cable model, as shown in Figure 118, which has similar structure to a full-scale cable model but a shorter length.

The current LS-Dyna cable model consists of solid elements and beam elements. The solid elements represent the actual geometry of the cable and handle the contacts with errant vehicles. The beam elements are placed in the middle and are wrapped around by the solid elements, as shown in Figure 119. The cable is modeled with deformable materials, except the two very ends. The two ends are modeled with rigid materials and both are pinned at the centers.

The baseline model consists of 6 parts, as shown in Figure 118. Parts 5011 and 5015 were rigid bodies, and the rest were deformable. All of the parts were modeled with solid elements, except part 9018, which was the beam embedded in the cable. The two ends were fixed in all translational directions but were allowed to rotate in the X-Z plane. Three nodes on the cable (Node 5116472-left end; Node 5116539-middle point; Node 5116611-right end) were picked to monitor the cable’s deflection in the Z (vertical) direction. Three cross-sections (gray planes in
Figure 118) were chosen to monitor the force change in the cable. The cross-section force stabilized around 40 kN after oscillation, as shown in Figure 120.

**Figure 119. Cable Model Compositions**

**Figure 120. Cross-Section Forces vs. Time in Baseline Model**
Figure 121. Node Vertical Displacements vs. Time

After initial vibration, the middle point displacement of the cable stabilized around -5 mm, and the end points’ displacements were around 1mm, as shown in Figure 121.

In order to perform an accurate D2R switch, according to the findings in the previous analysis: (1) beam elements are not recommended to be switched; (2) each individual component needs to be merged with the master body to keep their original connections after switching to rigid bodies; (3) only one master body is needed due to the chain rule; (4) if a model initially has rigid component, the rigid component is recommended to be used as the master body, and its original constraint will be applied to the entire system after switching; and (5) the two rigid ends will be permanently merged together after D2R switch if no modifications are performed on the cable model. Or, in order to avoid the permanent merge, at least one of the rigid ends is to be remodeled as a deformable body.

Two switching methods (Rigid End Model and Deformable End Model) were applied on the cable model, and their results were compared with the baseline results to find a proper way of
D2R/R2D switching on the cable model. Three switching scenarios were designed to test the accuracy of D2R/R2D switches: (1) Case A: Rigid @ 0ms & Deformable @ 2ms; (2) Case B: Deformable @ 0ms, Rigid @ 2ms, and Deformable @ 6ms; and (3) Case C: Rigid @ 0ms & Deformable @ 0.1ms.

9.2.1 Rigid-End Model

In this approach, both ends were kept as rigid bodies. In order to keep the system’s original constraints, one of them was used as the master body and the other components were merged with it. The deck file of this switching approach is shown in Figure 122.

```
*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw pared
   9998                          0
$ nrbf ncsf rwf dtmax d2r r2d
    4
$
$ partID master
  5012  5011
  5013  5011
  5014  5011
  5015  5011
$
*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw pared
   9999                          2
$ nrbf ncsf rwf dtmax d2r r2d
    3
$
$ partID master
  5012
  5013
  5014
```

Figure 122. Input Deck of Rigid-End D-R Switch-Case A.
In Case A, the cable was switched to rigid at 0 ms and was switched back to deformable at 2 ms. The initial force was constant because the solid cable was switched to a rigid body. After
the solid cable was switched back to a deformable body at 2 ms, the gravity started to deform the
cable and the cross-section force finally stabilized around 40 kN, which was the same as in the
baseline model.

The history of the cable’s deflection in Case A is shown in Figure 124. The deformation
was zero between 0 ms and 2 ms as expected. After the cable was switched back to a deformable
body, the deflection of the middle point stabilized around -5 mm, which was the same as the
baseline model. However, no displacements of the two ends points were observed during the
entire switching process.

Figure 125. Cross-Section Forces vs. Time in Case B
In Case B, the deflection of the cable due to gravity until time 2 ms was exactly like the baseline model. The cable was then switched to rigid bodies, and the cross-section force stayed constant until the solid cable was switched back to a deformable body at 6 ms. Then, the gravity again deformed the cable, and the cross-section force finally stabilized around 40 kN, and the middle point finally stabilized around -5 mm. Thus, both the final cross-section force and the final deflection were the same as in the baseline model.

However, the cable structure was noticed to have more damped behavior after the D-R switch. The baseline model took about 11 ms to stabilize around 40 kN (Figure 120), but the cable after D-R switching stabilized more quickly than the original structure.
Case C was a quick D-R switch. The results were expected to be almost exactly like the baseline. As shown in

Figure 127 and Figure 128, the results are similar to the baseline but not the same. The final force was around 40 kN, and the final middle-point deflection was around -5 mm. Both of
the cross-section force and the maximum deflection were the same as observed in the baseline model. However, Case C had less vibration than the baseline model before the cable reached its stability. And the end nodes still had no deflections after switching back to deformable bodies.

Based on the results from Case A, Case B, and Case C, the D-R switch did not change the cable’s deformation or internal force level, but the cable’s end movements were changed by the D-R switch. The behavior difference was caused by the permanent merge of the two rigid ends. As previously pointed out, if multiple rigid components initially exist in a model, they are permanently merged together and cannot be separated after D2R switching. In the original baseline model, both ends of the beam were initially rigid and pinned at their C.G. locations. Thus, both of the ends can rotate around their C.G due to the gravity. However, after switching to rigid, the original boundary conditions cannot be recovered. Both ends are merged as one piece of rigid body after D2R switching and cannot be separated as individual components again. The original pin-constraint on the master rigid body was applied on the merged rigid body, resulting in the loss of the rotational freedom at the ends of the cable (Figure 129 b). This explained the straight curves in Figure 128, and also explained why the switched structure can damp out more quickly than the original structure.

Figure 129. Boundary Conditions were changed after switching
However, D-R switches on a rigid-end model presented fairly accurate results in terms of the deflections and cross-section forces. Neither the cross-section force nor the deflection was affected by the D-R switch, as shown in Figure 130.

Figure 130. Cable Vertical Deflection Comparisons
9.2.2 Deformable-End Model

In order to avoid the permanent merge of the two ends and recover the original constraints after D-R switch, the two rigid cable ends were modified to deformable materials instead of rigid materials. Pin constraints were implemented by using single point constraints on the aligned nodes along the Y axis through the C.G. location, as shown in Figure 131.

![Figure 131. Illustration of “Deformable Ends” Model](image)

The two ends were modeled using *MAT_ELASTIC, but with extremely large stiffness (E=10000 GPa). Using this method, the cable’s behavior was very close to the baseline model. Deflections and forces are shown in Figure 132 and Figure 133. Though there were slight differences, this deformable end model could still be acceptable, since there is no absolutely rigid body in real life.

In this switch method, the two ends and the beam were kept as deformable, and all of the other parts were switched to rigid bodies. Since the two ends are connected with the rest of the cable using merged nodes connection, they can still be connected without being switched to rigid. Thus, the original rotational constraints can be kept. The corresponding input deck was modified as shown in Figure 133.
Figure 132. Deflection Comparison between Rigid-End and Stiff-End Models

Figure 133. Cross-Section Force Comparison
The results of the D-R switch of this Deformable-End model are plotted in Figure 135 and Figure 136. This showed that the deformable parts could be smoothly switched back and forth without affecting the results of either the cross-section forces on the deflections.

Figure 134. Input Deck of D2R/R2D Switching for Stiff-End Model

Figure 135. Deflection Comparisons of Different Cases
9.3 Full-Scale Model Switch

Based on the simplified model analysis, though the Deformable-End approach can recover its original status after the D-R switches, the Rigid-End approach was determined to be applied on the full-scale model. This is because the nodal constraints on the deformable ends might become unstable when the large load was applied, and meanwhile the effect of fixed ends was negligible for the full-scale cable system.

A baseline full-scale cable model was built, as shown in Figure 137. The rigid ends of the cables were fixed in both of the translational and rotational freedoms. The cables were straight initially with gravity applied in the z-direction.
The cables gradually deformed over time due to gravity. It took 8 CPUs on the UNL prairiefire machine about 17 hours to stabilize the baseline model. The maximum deflection was 5030 mm (198 in.) at the mid span. Considering the symmetry of the cable, only three points (The End: Node #5116468, The Quarter Point: Node #5127667 and the mid-span Node #10390014 ) were picked to monitor the cable’s deflection. Meanwhile, five Cross-Sections were also used to monitor the Cross-Section forces in the cables, as shown in Figure 137. The results from the baseline model are shown in Figure 138 through Figure 139.

Figure 138. Baseline Cable Deflection vs. Time
Figure 139. Baseline Cable Cross-Section vs. Time

The application of R2D and D2R on the full-scale cable model is shown in Figure 140. The originally deformable solid elements were switched into rigid parts at time 100 ms and then were switched back into deformable at time 500 ms. Simulation was terminated once the cable totally stabilized after being switched back to deformable bodies.

According to the short-cable study above, one of the originally rigid ends of each cable was used as the master body during D2R, and all of the other parts were merged with this master body when they were switched to rigid bodies. Thus, all of the originally deformable parts (parts # 5007 through 5009) of the cables were switched back to deformable bodies and maintained their original connections with the adjacent parts, while the other rigid end of each cable (Part #. 5010) was still merged with the master-body rigid end (Part # 5006). The histories of the cables’ deflections and cross-section forces are shown in Figure 141 and Figure 142. Comparison with
the baseline model results showed that the D2R model had a fairly good agreement with the baseline model in terms of both the vertical deflection and Cross-Section force, which proved that the D-R switch didn’t affect the cable’s performance at all.

*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw paried
 9998 100
$ nrbf ncsf rwf dtmax d2r r2d
$$
$ partID master
 5007 5006
 5008 5007
 5009 5008
 5010 5009
$
$
*DEFORMABLE_TO_RIGID_AUTOMATIC
$ swset code time1 time2 time3 entno relsw paried
 9999 500
$ nrbf ncsf rwf dtmax d2r r2d
$$
$ partID master
 5007
 5008
 5009
$

Figure 140. LS-Dyna Deck File of D2R and R2D
Figure 141. Cross-Section Forces Comparison of Baseline Model and D-R Model
Figure 142. Vertical Deflection Comparisons of Baseline Model and D-R Model
9.4 Summary

The preliminary cable model has insufficient bending stiffness. It presents unrealistic deflection due to gravity. A proper implementation of a D-R switch can fix the problem efficiently without adding extra complexities to the original cable model.

The D2R and R2D switches were first performed on a small-scale high-tension cable system to find out a proper switching approach. Two approaches were tested. One approach did not modify the original cable structure but lost the pivot movements on the cable ends after switching. The other approach remodeled the two ends as deformable components to keep the original end constraints after switching. Both approaches showed good agreement with the baseline model by comparing both the vertical deflection and cross-section forces.

The rigid-end approach was chosen to be applied on the full-scale cable system model, because the effect of merged ends is negligible for the full-scale cable model. Results proved that the cable’s performance was not affected by the D2R and R2D switches. Thus, it is believed that the combination of D2R and R2D is an efficient way to improve the cable model.

Proper use of D2R and R2D can counteract the poor deflection of the cable model due to its inaccurate bending stiffness. The deformable cable model can be switched to a rigid body from time zero until it is necessary to be deformable. By switching the initially deformable parts into rigid bodies, the cable can be kept straight under gravity even without any post models, which matches the real life and also benefits the future research by offering a simplified-and-accurate cable model.
10 APPLICATION OF D2R/R2D ON TRUCK RUN-OFF-SLOPE

For some simulation scenarios, it is not necessary for a vehicle model to be deformable throughout the calculation. Proper switching of the vehicle between deformable status and rigid status can improve the simulation’s efficiency without significantly affecting the results. In this chapter, investigations were performed to apply D2R and R2D switches on the current MwRSF C2500 pickup truck model for a running-off-slope simulation while following the D-R procedure developed in Chapter 8.

10.1 Baseline Model Description

Figure 143 is the baseline model set-up. A pickup truck runs off a slope at a speed of 100 km/h (60.2 mph) at an angle of 25 degrees, and lands on the sloped ground followed by a flat ground.

Figure 143. Pickup Truck Runs Off Slope

The current C2500 MwRSF pickup model was used for the simulation. The entire simulation lasts 1200 ms, which takes 22,521 seconds using eight CPUs on the prairiefire cluster.
at University of Nebraska-Lincoln. The vehicle's trajectories and energy changes are plotted in Figure 144 through Figure 145.

![Figure 144. Sequential of Vehicle Running Off Slope](image-url)

10.2 Implementation of the D-R Switch

As shown in Figure 144, the vehicle performed rigid-body movement when it was airborne after leaving the sloped edge. The deformation of the vehicle’s body was negligible, except for the vibration and rebound of the suspension system. Therefore, the simulation time can be shortened if the vehicle is switched to rigid during the airborne time and is switched back to a deformable body before landing on the lower ground. A D-R switched was performed on the vehicle model while following the developed procedure.
Figure 145. Simulation Results of the Original C2500 Pickup Model Runs Off Slope
10.2.1 Step 1-Whether to Switch All of the Components

According to the procedure, the first step is to determine whether the D-R is going to include all of the components. Because the suspension and tire still have relative displacements when being airborne, as shown in Figure 146, the switch of the vehicle system will exclude the suspension and tire system and only applies to the sprung mass components.

Figure 146. Suspension and Tire Systems in C2500 Pickup Model

Figure 147. The To-Be-Switched Components in C2500 Pickup Model
10.2.2 Step 2-Check Connections

Since it was determined not to switch all of the components, the next step was to check the connections that connect the to-be-switch components and the deformable components. A thorough investigation of the MwRSF C2500 pickup truck model structure was conducted. Besides the suspension and tire systems, the vehicle consists of 53 parts. The parts are connected to each other using five different types of connections. Figure 148 is an illustration of the current C2500 pickup model’s compositions and their interactions. The above-suspension components are connected to the suspension through merged-nodes connections. The merged-nodes connections allow the above-suspension components to be switched to rigid while keeping the suspension components deformable all the way through the calculation.

10.2.3 Step 3-Inter-Component Connection Check

As shown in Figure 148, there are five connection types used in the pickup model: Merged-Nodes, Nodal-Rigid-Body-Constraint, Spot-Weld, Extra-Nodes-On-Rigid-Body, and Contact-Tied-Nodes-To-Surface connections. According to the findings in Chapter 4, most connections can be kept and recovered if the components are merged with a master rigid body during D2R, except Contact-Tied-Nodes-To-Surface connections.

The cargo box (Part #95) is connected to the vehicle frame cross bar top surface (Part #102) using Contact-Tied-Nodes-To-Surface connection. To keep the connections and avoid calculation errors, one of the two components connected by the Contact-Tied-Nodes-To-Surface connection needs to be kept as deformable. In order to determine the component that should be kept as deformable, all of the connections on parts #102 and #95 have to be taken into consideration. Both parts #95 and #102 are connected to other components using merged-node connections, which allows either of them to be kept as deformable without affecting other to-be-
switched components. Considering that the size of part 95 is much bigger than part 102, it was decided to maintain the smaller part (Part #102) as a deformable body and switch the larger part (Part #95) to a rigid body to improve the simulation efficiency.

10.2.4 Step 4-Check Element Types

No Type 1 Shell, Type 6 Shell, or Type 3 Solid elements were found in the model.

According to the simple-model findings, all of the 1-D element components should be excluded from the D-R switch. Parts 79, 80, 275, and 276 are modeled with 1-D elements, as shown in Figure 148. The wheel-well-and-cargo-box connections (Part #79) and rear lateral rail connecting two longitudinal rails (Part #80) were modeled using beam element, as shown in Figure 151. Meanwhile, both of Parts #79 and #80 are connected to their related components using merged nodes. The merged-node connection make it possible for part #79 to be deformable when both the cargo box and wheel well are switched to rigid bodies; and Part #80 can also be kept as deformable materials when D2R switching is applied on the longitudinal rails.
Figure 148. Component Connections (Above Suspension) of C2500 Pickup Model
Figure 149. Connection between Cargo-Box and Cross-Rail Top Surface

Figure 150. Top Surface Shared Nodes with Cross Rail

Part #79 Beam

Part #80 Beam

Figure 151. Beam Components in C2500 Pickup Model
10.2.5 Step 5-Boundary Condition Check

No single point constraints were found in the to-be-switched components. And the vehicle’s movement was defined by the initial velocity, thus the vehicle’s motion would not be affected by the D-R switch.

10.2.6 Choice of the Master Body

The master body was recommended to be chosen from the initial rigid bodies, and the proper choice also depends on the boundary conditions. There are multiple rigid components in the current C2500 model, as shown in Figure 152. Since none of them has special boundary conditions or constraints that controlled the entire vehicle’s movement, any of them can be used as the master body and will not result in any differences, according to the simple-model investigations. The engine block (Part #7) is used as the master body for D2R switch herein.

Figure 152. Initially Rigid Bodies in C2500 Pickup Truck Model
10.3 D2R Switch-Rigid Rail

For the first D2R switch conducted, all of the above-suspension components were switched to rigid bodies, excluding the beam components noted by Parts #79, #80, and cross rail top Part #102. To keep and recover their original connections, all of the components were merged with the master body (Engine Part #7). The vehicle was switched to a rigid body at 300 ms when the last tire (right-rear tire) left the edge of the slope. Next, the vehicle was switched back to deformable at time 1200 ms, right before the first tire landed on the ground. The corresponding switching deck file is listed in Appendix B.

The simulation run time was reduced to 2.28 hours, compared to the baseline’s run time of 6.25 hours. The vehicle’s trajectories, energy change, and C.G. movement were compared against the baseline model results, as shown in Figure 153 through Figure 156.
Figure 153. C.G. Trajectories Comparison with Baseline Model
Figure 154. C.G. Rotation Comparison with Baseline Model
The switched model presented good agreement with the baseline model until about 800 ms, when the vehicle already landed on the lower ground and was switched back to deformable. The pickup’s C.G. vertical displacement (the right of Figure 153) and its longitudinal rotation (the right of Figure 154) showed obvious discrepancy from
The baseline results after D2R and R2D switches, which was also observed in the internal energy history (Figure 156).

The differences were caused by the permanent merge after the D2R switching in the pickup truck model. According to the irreversible rigid merging rule, if a system has multiple initially rigid bodies, they will be permanently merged together after a D2R switch. Thus, all of the rigid parts in Figure 152 were still connected together after the other components were switched back to deformable bodies.

The suspension joint brackets, where the suspension connects to the vehicle body, were all defined as rigid bodies (see Figure 157). In the baseline model, when the pickup truck landed on the ground, there were relative movements between these suspension joints, especially between the two longitudinal rails. However, after the D2R was applied, all of the brackets were merged together. They moved as one piece of rigid body and cannot be separated after the R2D switch. Thus, there was no relative movement between these brackets. All of the suspensions behaved as if they were supporting one piece of rigid body, which reduced the vehicle’s flexibility and resulted in the differences noted.

Figure 157. Suspension Joints are Permanently Merged after D2R Switch
10.4 D2R Switch-Deformable Rail

Next, a different switch method was conducted in order to avoid the permanent merge and reduce the discrepancy after switching back to deformable. One way to avoid the permanent merge was to keep the rail frame deformable.

Whether the rails can be maintained as deformable bodies is determined by the connection types between the rails and the related components. It was found that all of the components were connected to the rails either through Nodal-Rigid bodies or Merged-Nodes. The front suspension arm brackets (part # 35 and part # 36) are connected to the vehicle rail (part #2) using merged nodes, as shown in Figure 159, and the rear suspension brackets are connected to the rail through Nodal-Rigid body-Constraint. The vehicle body connects to the rails through the body mounts, and the mounts are connected to the rails using merged nodes.

Figure 158. Vehicle Rail and the Connected Parts
Both the Nodal-Rigid body Connection and Merged-Node Connection allow the frame rails to be kept as deformable and are still connected to the vehicle body, while the rest of the vehicle body is switched to rigid bodies. Since the rails are not switched to rigid, all of the suspension brackets on the rails can keep their original connections with the rails, and they do not have to be merged with the master rigid body. Thus, the
suspension brackets are still separated from each other after the vehicle landed, and they still have relative movements between each other when the vehicle lands. The results are compared with the baseline results and are plotted in Figure 162 through Figure 165. All of the results present good agreement with the baseline results. Thus, by keeping the rail’s deformability, the vehicle’s performance was not changed after D2R/R2D switches.

Figure 162. C.G. Trajectories Comparison with Baseline Model

Figure 163. C.G. Rotation Comparison with Baseline Model
Figure 164. Kinetic Energy Comparison with Baseline Model

Figure 165. Internal Energy Comparison with Baseline Model

10.5 Summary and Conclusion For Truck-Slope Example

When a vehicle runs off a slope, most of its components act like rigid bodies when the vehicle is airborne. Properly switching these components to rigid and back to
deformable can significantly improve the simulation efficiency without affecting the simulation’s accuracy, as shown in Table 8.

Table 8. Switching Model Comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>Baseline</th>
<th>Rigid-Rail Switch</th>
<th>Deformable-Rail Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cpu Time (sec.)</td>
<td>22521</td>
<td>8217</td>
<td>8621</td>
</tr>
<tr>
<td>Improved Efficiency</td>
<td>NA</td>
<td>63.5%</td>
<td>61.7%</td>
</tr>
</tbody>
</table>

Investigations of D2R/R2D switches began with the analysis of the current vehicle model structure, including the vehicle models’ element types, connections, initial rigid bodies, boundary conditions, etc. Based on the previous simple model findings, in order to avoid instability during D2R switching, those components that are modeled with beam elements are kept as deformable bodies throughout the simulation. Also, one of the components that is connected by *Contact-Tied-Nodes-To-Surface is not included in the D2R switch.

Two different switching approaches were applied on the model: the frame rails were switched to rigid in the first approach, while they were kept deformable in the second approach. The pickup truck was switched to rigid between 300 ms and 700 ms when it was airborne. Both switching approaches reduced the simulation time, as shown in Table 8, and showed good agreement with the baseline model during the airborne period, as shown in Figure 166 through Figure 168.
Figure 166. C.G. Rotation Comparison

Figure 167. C.G. Trajectories Comparison
Figure 168. Internal Energy Comparison

Since there are multiple initial rigid bodies in the vehicle model, to keep their connections to the rails, they had to be merged with the master body after the rails were switched to rigid bodies. Thus, they were permanently merged with the master rigid body and could not be separated again when the other components were switched back to deformable bodies. The permanent merge eliminated the relative movements between each suspension joint in the vehicle and resulted in discrepant behaviors after landing on the ground.

To fix the inaccurate suspension system movements after landing, the second switching method excluded the frame rails from the D2R switch. The rails were deformable throughout the simulation, while the rest of vehicle body was switched to rigid. In this way, all of the rigid suspension brackets can still maintain their own original connections with the rails without merging with the master body. So the suspension had
the same behaviors as the baseline model after landing on the ground, which presented more accurate simulation results.

Thus, the second (deformable rail) switching approach is recommended due to its better accuracy than the first (rigid rail) approach and similar efficiency.
11 SUMMARY AND CONCLUSION

In order to improve the simulation efficiency, the components that experience negligible change of deformation/stress can be modeled with rigid bodies. However, the implementation of rigid bodies is always restricted for a simulation consisting of multiple events, because the use of rigid bodies has to satisfy every single event in the simulation. Meanwhile, for the complicated models, less rigid bodies are preferred in order to avoid duplicated modeling efforts, while more bodies are preferred for the particular simulation task. Thus, in order to maximize the use of the rigid bodies and improve the simulation efficiency, it is desired to switch the components between the rigid status and the deformable status when it is deemed necessary.

Several commands are currently available in LS-Dyna to perform the switch between the deformable and rigid statuses. Though there is a rising demand for the use of deformable and rigid switches, little research has previously been performed to clarify the implementation of the switches.

The investigation herein started with the comparison of the current switching commands in LS-Dyna. The features of each switching command were summarized and implementation examples of each command were provided. Among the switching commands, *Deformable_To_Rigid_Automatic was recommended for general use due to its flexibility in terms of switch activation and easy application.

Then, investigations based on the simple models were performed to identify the key factors for the D-R switch. The results revealed that the D-R switch could be affected by the choice of element, the boundary conditions, the inter-component connections, mass change, proper master body choices, etc.
Beam elements are not recommended for D2R/R2D switches in order to avoid instabilities. Any shell element that is derived in global coordinates should not be used for the D-R switch. For solid element, fully integrated solid with nodal rotations (Type 3) will cause instability in the D-R switch too.

Since the connections between deformable bodies are usually incompatible with rigid bodies, the connections might possibly result in calculation errors in the D-R switch if they are not properly treated. Investigations show that merging with a master rigid body is the most reliable way to keep the components connected after being switched to rigid bodies. Also, by merging with the master body, the original connections between rigid bodies can be immediately recovered when the components are switched back to the deformable status.

Unrealistic mass increases were noticed when deformable components were switched to rigid. Investigations found the mass increase was because of the connections on the component, some of the connection nodal mass is also counted into the new rigid body when the component is switched to rigid. For a large-scale model, the mass change is usually negligible. If the mass change cannot be neglected, the mass of the new rigid body should be manually defined using the command of *Deformable_To_Rigid_Inertia instead of calculating from the existing mesh nodes. However, the mass change only occurred when the model was partially switched to rigid. If all of the components in a model were switched to rigid body and were merged with the master body, no mass change was observed.

The use of a master body is recommended for the D-R switch in order to keep the original inter-component connections and to avoid the inaccurate mass increase.
Investigations revealed that only one master body is needed no matter how many components are in the model. All of the other components can be directed merged with the master body even if they are not originally directly connected to each other. If a model has a initial rigid body, the initial rigid body had to be used as the master body. If there are multiple initial rigid bodies in the model, the choice of master rigid body is controlled by the boundary conditions of these rigid bodies. The rigid body that bears the critical boundary condition/constraint for the entire system has to be defined as the master body.

The boundary conditions and movement descriptions of deformable components are applied on the nodes for deformable components, while descriptions of rigid bodies are based on the C.G. location. Potential issues could happen if the boundary conditions are not properly treated in the D-R switch. Investigation showed that the single-point constraint is unstable during D2R switching in LS-Dyna. Components that have single point constraints should not be included in D2R switches, or, the single point constraints should be replaced with proper constraints if the component is to be switched to rigid. Initial velocity applies the motion on the nodes of the deformable component, and this nodal motion field is saved when the deformable component is switched to rigid body; then the C.G. motion of the newly formed rigid body is calculated from the saved nodal motion field, and all the nodal motion values will be reset correspondingly based on their position with respect to the C.G. location; If prescribed motions are applied, the prescribed motion will be deactiviated by LS-Dyna when a D2R switch is applied, while the nodal motions before are saved. The C.G. motion of the new rigid body is calculated based on the saved nodal motion field, and the nodal motions of the rigid body are reset
to this calculated value. Both initial velocity and prescribed motion can be smoothly transitioned between deformable and rigid statuses for translational movement, while disturbance occurred for rotational movements.

Based on the simple-model findings, a procedure was developed for the D-R switch in order to guide users to apply the switches properly in LS-Dyna simulations. Two examples were provided to demonstrate the implementations of the D-R switching procedure and to show the improvement of the efficiency through the use of D-R switching. In the first example, the D-R switch was applied on a cable model to compensate for the lack of the bending stiffness and to shorten the initial stabilization time. In the second example, by following the D-R procedure, the simulation time of the vehicle running off a slope was significantly reduced. Both of the examples proved the proposed D-R switching procedure was correct.
12 REFERENCES

APPENDIX A Baseline Model Deck File For Pendulum Impact

*KEYWORD
*TITLE
Pendulum with 2 spheres colliding
$
$ - uses *DEFORMABLE_TO_RIGID option to decrease execution time before impact
$ - one sphere is given an initial velocity (gravity alone just takes
$ too long for the pendulum to swing)
$ J.D. Reid 6/22/95, 4/7/98
$ $ - Changed contact type to *Contact_Automatic_Surface_To_Surface
$ - Refine the sphere mesh
$ - Soften sphere material
$ - Slow down impact speed
$ L.Zhu 09/30/2008
$ $ Units: mm, kg, ms, kN, GPa, kN-mm
$ $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$ $...
$ $...>....1....>....2....>....3....>....4....>....5....>....6....>....7....>....
$ $ *CONTROL_TERMINATION
$ $ endtim endcyc dtmin endeng endmas 30
$ *CONTROL_ENERGY
$ $ hgen rwen slnten rylen 2 2
$ *CONTROL_OUTPUT
$ $ npopt neecho nrefup iaccop opifs ipnint ikedit 1 3
$ *CONTROL_SHELL
$ $ wrpang itrist irnxx istupd theory bwc miter 1 2
$ *CONTROL_TIMESTEP
$ $ scft 0.6
$ *DATABASE_BINARY_D3PLOT
$ $ dt lcdn 1.00
$ $ 0.1
$ *DATABASE_EXTENT_BINARY
$ $ neigh neips maxint strflg sigflg epsflg rltflg engflg
$ cmpflg ieverp beamip
  1
$
*DATABASE_BINARY_D3THDT
$    dt    lcdt
    999999
$
*$DATABASE_GLSTAT
$    dt
    0.10
$
*$DATABASE_MATSUM
$    dt
    0.10
$
*$DATABASE_NODOUT
$    dt
    0.10
$
*$DATABASE_HISTORY_NODE
$    define nodes that output into nodout
$    id1    id2    id3    id4    id5    id6    id7
    id8
    350    374    678    713
$
*$DATABASE_RBDOUT
$    dt
    0.10
$
*$DATABASE_RCFORC
$    dt
    0.10
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$$$$  Define Contacts - Sliding Interfaces
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
...>....1....>....2....>....3....>....4....>....5....>....6....>....7....>....
$
$
*$CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID
$    cld    heading - columns 11-80
    99
$
$    ssid    msid    sstyp    mstyp    sboxid    mboxid    spr
    mpr
    1    2    3    3
$
$    fs    fd    dc    vc    vdc    penchk    bt
dt
$
$
$    sfs    sfm    sst    mst    sfst    sfmt    fsf
vsf
$$\text{optional card A}$$

$$\text{soft sofscI lcidab maxpar edge depth bsort}$$

$$\text{frcfrq}$$

$$\text{Gravity}$$

$$\text{Boundary and Initial Conditions}$$

$$\text{Constrain translation of end points of beams}$$

$$\text{BOUNDARY_SPC_NODE}$$

$$\text{initial velocity}$$
$ vx    vy    vz    wx    wy    wz
  0.0   -6.0   0.0
$

*DEFINE_BOX
$ boxid  xmm  xmx  ymn  ymx  zmn  zmz
  5  -120.0  -80.0  80.0  120.0  -30.0   30.0
$

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$$ Define Parts and Materials $$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$...>....1....>....2....>....3....>....4....>....5....>....6....>....7....>....
8
$

*PART
$ pid    sid    mid    eosid    hgid    grav    adpopt
sphere1   1    1    1
sphere2   2    2    1
$

$$$$ Materials $$ sphere
*MAT_ELASTIC
$ mid    ro    e    pr    da    db    k
  1  7.86e-6   50  0.30
$

$$$$ Sections $$

*SECTION_SHELL
$ sid    elform    shrf    nip    propt    qr/irid    icomp
  1    2
$

$ t1    t2    t3    t4    nloc
  1.0    1.0    1.0    1.0
$

*SECTION_SHELL
$ sid    elform    shrf    nip    propt    qr/irid    icomp
  2    2
$

$ 1.0    1.0    1.0    1.0
$

$$$$$$ PENDULUM WIRES - ELASTIC BEAMS $$

*PART
Pendulum Wires - Elastic Beams
$ pid    sid    mid    eosid    hgid    grav    adpopt
  45    45    45
$

*SECTION_BEAM
$ sid    elform    shrf    qr/irid    cst
  45    3    1.00000   1.0
$

$ int: ts1    ts2    tt1    tt2    nsloc    ntloc
$ res:  a   iss   itt   irr   sa
       10.0
$ disc: vol  iner  cid  ca  offset
$   t1  t2  t3  t4  nloc
$
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$  mid  ro  e  pr  da  db  k
   45  7.86e-6  210.0  0.30
$
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$
$ Define Nodes and Elements
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
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APPENDIX B Input Deck for C2500 Switch-Rigid Rail

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2 frnt-brckt 7
3 whouse 7
4 rr-bumper-bracket 7
5 rr-bumper-flange 7
6 rear-bumper-cover 7
7 rr-bumper 7
8 rr-bumper-xbar 7
9 bed-outter 7
10 bed-inner 7
11 bed-well 7
12 cabin-mnt 7
13 cab-- 7
14 glass 7
15 left door 7
16 right door 7
17 fan 7
18 hood 7
19 rad-tie2 7
20 rad-tie3 7
21 bumper 7
22 oilbox 7
23 fender-outter 7
24 fender-inner 7
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### APPENDIX C Input Deck for C2500 Switch-Deformable Rail

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$2 frnt-brckts
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$3 whouse
    14    7
$4 rr-bumper-bracket
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$5 rr-bumper-flange
   100    7
$6 rear-bumper-cover
   110    7
$7 rr-bumper
    98    7
$8 rr-bumper-xbar
   101    7
$9 bed-outter
    69    7
$10 bed-inner
    95    7
$11 bed-well
    96    7
$12 cabin-mnt
    22    7
$13 cab--
    21    7
$14 glass
    89    7
$15 left door
    23    7
$16 right door
    24    7
$17 fan
    9    7
$18 hood
    10    7
$19 rad-tie2
    16    7
$20 rad-tie3
    17    7
$21 bumper
     1    7
$22 oilbox
     8    7
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*END*