Investigations of Generalized Joint Stiffness Model in LSTC Hybrid III Rigid-FE Dummies

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Abstract

*The joint restraint model *CONSTRAINED_JOINT_STIFFNESS_GENERALIZED in LS-DYNA® provides users a way to define stiffness characteristics for joints defined by *CONSTRAINED_JOINT_OPTION. Based on the relative angles between two coordinate systems, moments are generated according to user-defined curves. It has been defined in LSTC Rigid-FE dummy models to describe the joint behaviors at limb joints such as hip, elbow and knee joints. There are two approaches in LS-DYNA® to calculate the relative angles, incremental update (default) and total formulation (option defined in *CONTROL_RIGID). In this paper, differences of the angular calculation of the two methods were investigated. In LSTC Rigid-FE dummy models, the default (incremental update) is used for the joint stiffness model. It demonstrates the shortcoming of the incremental update method for the joint that rotates about more than one axis. Consequently, joints at elbows and wrists in the Rigid-FE dummy models are limited to a single axis rotation, which are capable to rotate along two axes in a physical hybrid III dummy. Alternatively, a modified Rigid-FE dummy model with the total formulation method defined for the joint stiffness was then suggested.*

Introduction

The LSTC finite element (FE) models of HIII dummy family (95%, 50% and 5%) were first released in mid of 90s. They were based on the FE dummy database developed by Fredriksson [1]. There were two types of dummies in the release, deformable and rigid. The rigid model was a simplified version of the deformable one although it still contained many deformable materials. The noticeable difference was that the rubber materials between the discs in the neck were replaced by joints in the rigid model. In 2008, LSTC Hybrid III Rigid-FE dummy v1.0 was released to public, which was actually an improved version over the previous rigid dummy. This model was accompanied with a detailed user guide [2], which was missing in the early release. Kang's study concluded the LSTC Hybrid III Rigid-FE dummy model performed relatively well overall in frontal crash simulation [3].

Because it is faster and more reliable, the Rigid-FE dummy model provides great value in evaluating occupant restraint systems, interior structures and seating designs when prediction of occupant injuries is less critical. It is also suited for simulation in a long event such as a rollover, which might last over several seconds.

Users who have experience with the last released Rigid-FE dummy might notice that the elbow and wrist joints are limited to one rotational degree of freedom. The lower arm could only flex and extend. The torsion movement is not allowed. The angles reported in LS-PrePost® are sometimes confusing during dummy positioning. These shortcomings could be traced back to the original dummy database, which was created in LS-INGRID input format [4]. LS-INGRID was used to convert the dummy database into LS-DYNA input deck. Fredriksson defined Cardan restraints for various joints in the dummy database, which were thought to be the generalized

joint stiffness model in LS-DYNA. However, they were not the same nor were the Cardan restraints available in LS-DYNA at the time when Fredriksson developed the dummy database.

Generalized Joint Stiffness Model

In the generalized joint stiffness model, users can define an optional rotational joint stiffness for joints defined by * CONSTRAINED_JOINT_OPTION. Damping and friction are also optional. The most common joint is the spherical joint (* CONSTRAINED_JOINT_SPHERICAL), which has three rotational degrees of freedom. The revolute joint is often used with the generalized joint stiffness model though it only has one rotational degree of freedom.
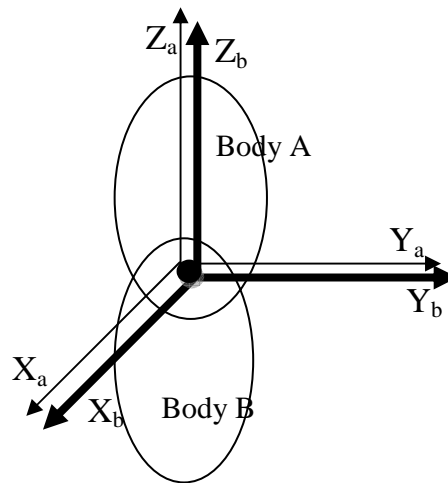

Figure 1 Generalized joint stiffness model

Figure 1 shows that rigid body A and body B are connected by a spherical joint. Two local coordinate systems are defined. Coordinate system A (X_a, Y_a and Z_a) is attached to first body A (or Parent) and coordinate system B (X_b, Y_b and Z_b) is attached to second body B (or Child). The two local coordinate systems are assumed to coincide initially. When the two rigid bodies rotate relative to each other, the two local coordinate axes no longer coincide. The relative angles ϕ, θ and ψ, are developed and torques are applied based on the defined load curves. If the initial coordinates (at time zero) do not coincide, the angular offsets will be initialized and torques will be developed instantaneously. Stop angles could also be defined. After the rotation angle reaches the stop angle, the defined elastic stiffness then is used to calculate the torque. One could constrain (or lock) certain rotational degree of freedom by defining small stop angles (i.e. +/-0.1 degree) with a large elastic stiffness value on that rotation axis.

In DYNA 971, there are two options to determine how the angles are calculated. They are incremental update (default) and total formulation (option). The option can be specified with parameter JITF in *CONTRAL_RIGID.

Since the generalized joint stiffness (the default method) was added to LS-DYNA in 1993-1994, it has gone through some developments over the years. The option, total formulation, was formally introduced in Version 950 in 1998. In this paper, discussions and examples were based on the current Version 971.
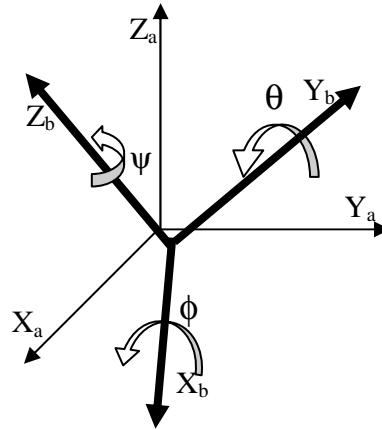
Figure 2 Rotation axes in incremental update (default) method

a) Incremental update (Default)

According to the User's Manual [5], "as the default, the calculation of the relative angles is done incrementally." To best understand how it works, the authors have done a series of test runs. It is speculated that LS-DYNA calculates the angular changes relative to the second coordinate system B at each time step and then accumulates them. The axes of the relative angles ϕ, θ and ψ are always attached to the second body B in Figure 2. When more than one rotational degree of freedom is defined, the user should be aware that the calculated angles are path dependent. Figures 3-4 show the same relative orientation (3c or 4c) would be obtained through different rotation sequences. In Figure 3, the second coordinate B rotates 90 degree about X_b in Figure 3a and then -90 degree about Y_b in Figure 3b. The same position could also be achieved by rotating Z_b by -90 degree in Figure 4a and X_b by 90 degree in Figure 4b. However, it is also noticed that the initial angular offsets in LS-DYNA are determined by Bryant angles with rotation sequences of ZYX. Angular offsets as 90 degrees of ϕ and -90 degrees of ψ would be initialized for the initial relative orientation of Figures 3c or 4c. This might lead to instability in some model setups. For example, in a generalized joint stiffness model with ψ rotation locked, if it is initially positioned as in Figure 3c or 4c, an undesired torque would be initialized on Z_b.
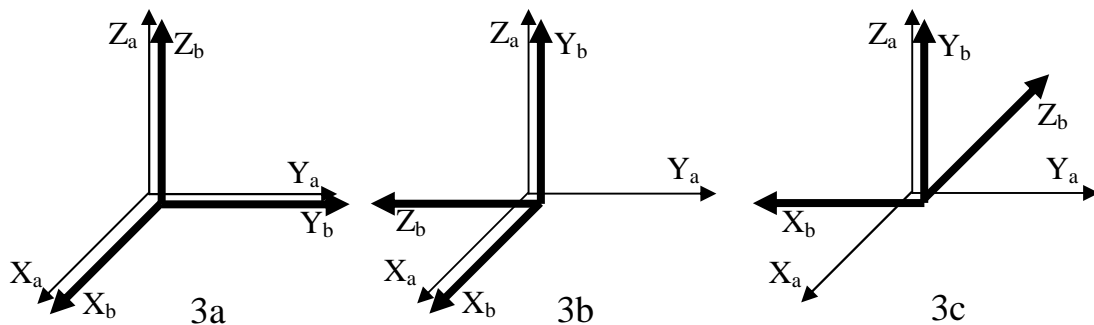
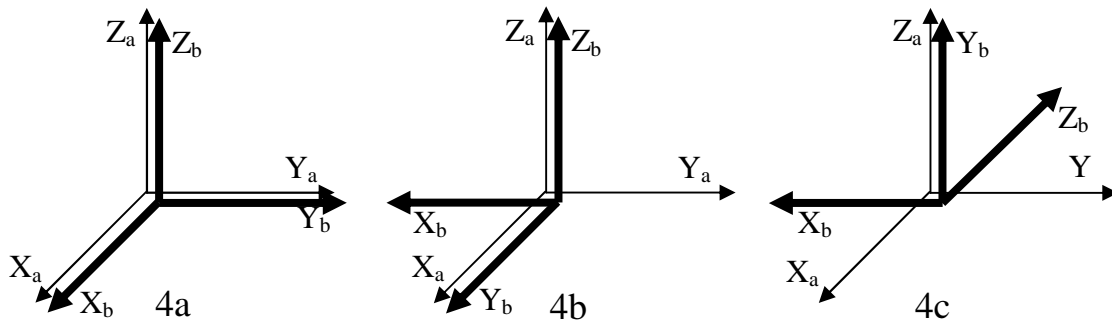**Figure 3 Rotation sequence: ϕ=90 degree, θ=−90 degree**

Figure 4 Rotation sequence: ψ=−90 degree, ϕ=90 degree

b) Total formulation (Option)

As the total formulation, the relative angles at each time step are computed according to Bryant or Cardan angles with rotation sequences of XYZ. The relative orientation of the local coordinate system is described in Figure 5. This type of restraint model is also referred to as a Cardan joint restraint.
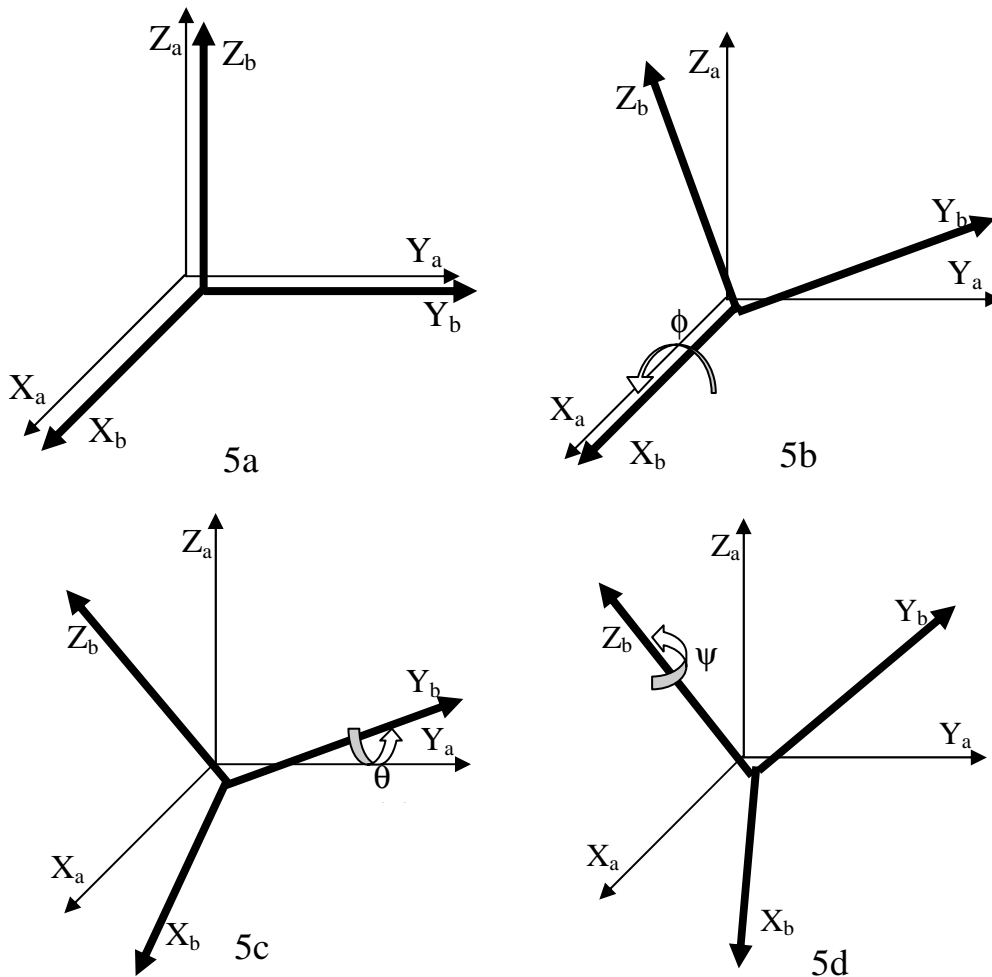

Figure 5 Rotation sequence of total formulation

In contrast to the default method where all three rotation axes are attached to the second body, with the option method, the rotation axis of ϕ is attached to the first body A and rotation axis of ψ is attached to the body B. Angle θ rotates about a floating axis. In the case where only two rotation degrees of freedom were allowed (i.e. one rotation is constrained or locked), one rotation axis would be attached to the body A and the other would be attached to the body B. For example, if the second rotation θ is locked, the rotation axis of the angle ϕ would be X_a on Body A and the rotation axis of ψ is Z_b on body B as shown in Figure 1.

One of the limitations for the optional method is that when $\theta = +/-90$ degrees, the first rotational axis or ϕ-axis and the third rotational axis or ψ-axis are parallel and the angles of ϕ and ψ cannot be discriminated. This is also called "gimbal lock". In an example shown in Figure 6, there is an initial offset of $\psi = 45$ degrees. An over -90 degree rotation movement about θ-axis was prescribed. The results show that there is a discontinuity in ϕ and ψ values when θ reaches 90 degrees. The angle θ should be limited to great than -90 and less than +90 degrees.
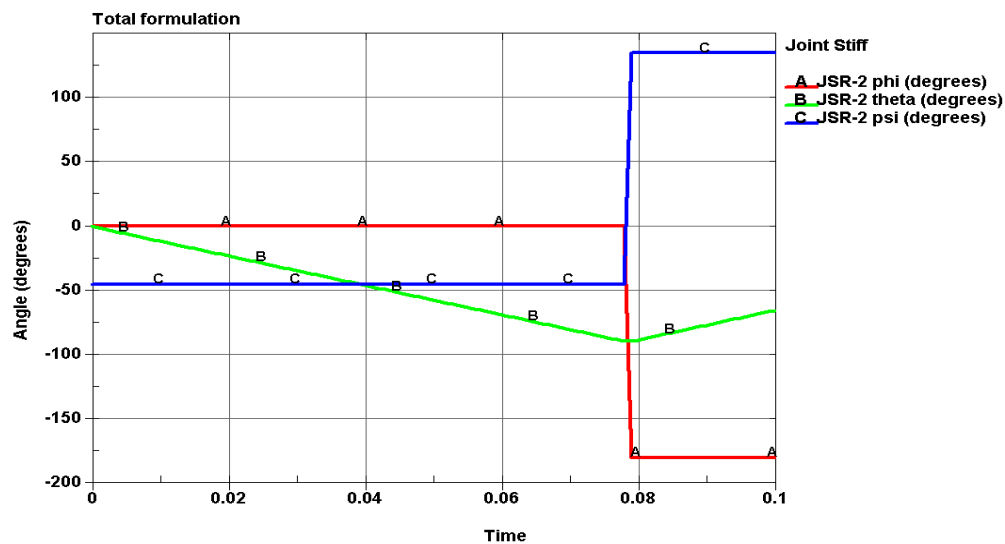

Figure 6 "Gimbal lock" in total formulation

Another limitation is that both ϕ and ψ are limited to range from -180 to +180 degree. Figure 7 shows the value of the angle ϕ when a continuous rotation of ϕ is applied. There is a discontinuity at 180 degrees. This shortcoming could be eliminated with future coding changes.

When only one rotation degree of freedom is allowed, the angular calculations in both approaches are identical with the exception of the angle limits in the total formulation. This is often the case when two rotation axes are locked, or the restraint model is defined for a revolute joint.

Generalized Joint Stiffness Model in Rigid-FE Dummies

The generalized joint stiffness model had been defined for various joints in Rigid-FE dummies. It greatly simplified the dummy model. The joint behaviors were characterized by user-defined load curves, which were obtained from tests. There was no need to model detailed structures of

the physical joints. It was also used for positioning the limbs initially. The generalized joint stiffness models that were defined for spherical joints are especially examined.
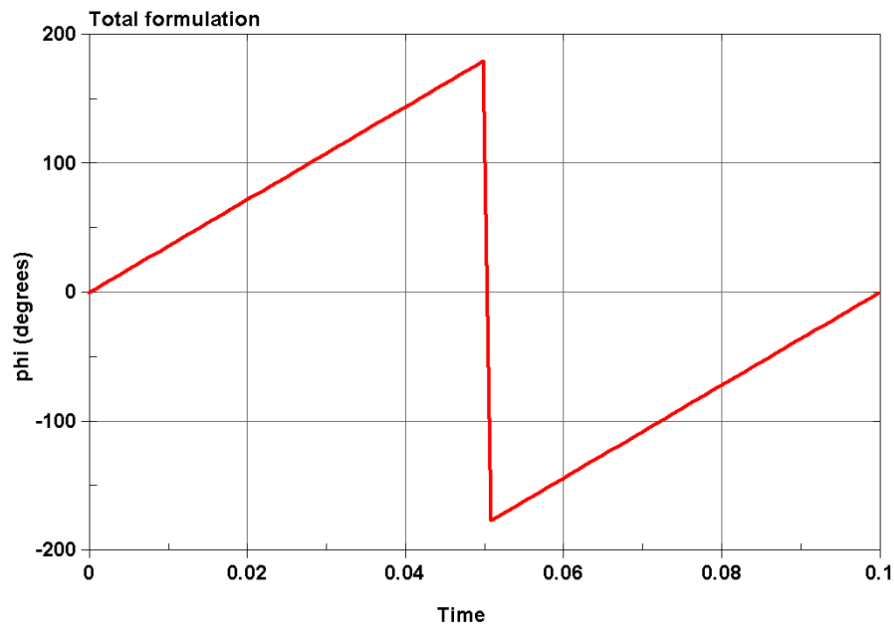

Figure 7 Singularity of angle ϕ

In the Rigid-FE dummy model, the default incremental method is used in the angular calculation of the generalized joint stiffness model. It is defined for series spherical joints in the Rigid-FE model. They are pair (left and right) of elbow, wrist and hip joints. The neck disks are also connected by a series of spherical joints.

Figure 8 shows an elbow joint of a physical HIII dummy. The lower arm can flex-extend as well as revolve around the upper arm in Figure 8a. The extension of the lower arm is stopped by a rubber stopper when it contacts with the metal in Figure 8b and the flexion is limited by the contact of arm vinyl covers showing in Figure 8c. The characteristic of the flexion-tension of the lower arm could be tested physically. Other than friction, there is no other restraint on the lower arm when it revolves around the upper arm. It's also interesting to notice that the axis of the torsion movement is always attached to the upper arm and the axis of the flexion-extension is on the lower arm.

Figure 9 shows an elbow joint model in the Rigid-FE dummy. If the degree of freedom of the joint had been set to allow the lower arm to rotate in both the ϕ and ψ axes, or XC and ZC (coordinate B or Child coordinate in LS-PrePost), rotation of XC would be fine as long as $\psi = 0$ as shown in Figure 9a. However, it would become unrealistic when the lower arm flexes in Figure 9b. The orientation of the ϕ axis or XC rotates with the lower arm. Rotation of ϕ is no longer physically possible. To avoid the problem, the degree of freedom of the elbow joints in the Rigid-FE dummies is limited to the flexion-extension rotation. With the default method, one fix could be to split the spherical joint into two revolute joints. In fact, when Fredriksson developed the original FE dummy database, he had observed this erroneous behavior of the lower arms. He had split the elbow joints into to two revolute joints. However, those changes

were not made to the early released FE dummy family. The similar problem also exists in the wrist joints.
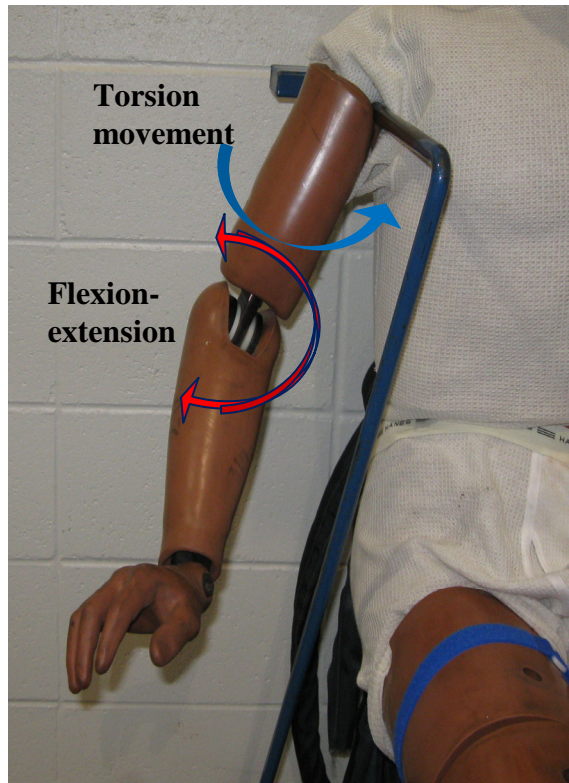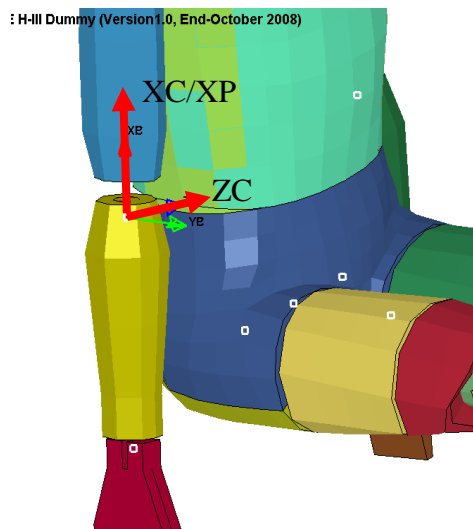

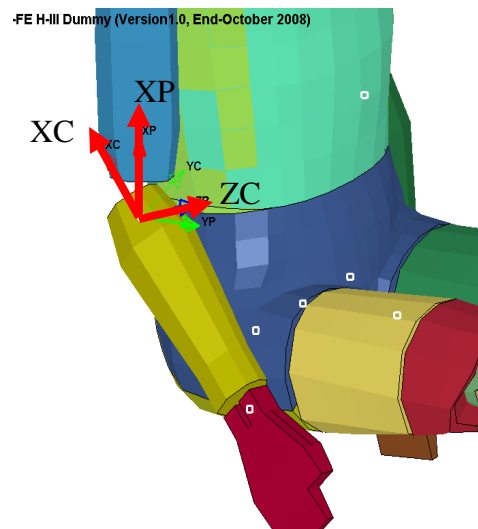**8a Lower arm movement**

8b Rubber stopper

8c Flexion stop limit

Figure 8 Elbow joint in HIII dummy

9a

9b

Figure 9 Elbow joint in Rigid-FE dummy model

The hip joints of the physical dummy are constructed with ball and socket joints and they have three rotational degrees of freedom. In the FE-Rigid dummy model, the torsion degree of freedom (along Y-axis) is locked and is not allowed to rotate in dummy positioning. It's often observed that the torsion angle occurs when the sequence of the rotation in the upper leg positioning changes. The angles reported in LS-PrePost often cause confusion.

On the other hand, the total formulation for the generalized stiffness model is a better approach to prescribe those joints. In Figure 9b, the orientation of the ϕ-axis is XP (Parent, or coordinate A) on the upper arm (body A) and the axis of the rotation ψ or the flexion-extension is ZC on the lower arm (body B). Because of the singularity of angle ϕ in current LS-DYNA, it is suggested that a large stop angle (i.e. +/-145 degree) be defined to prevent this occurrence.

At the knees, upper legs and lower legs are connected by revolute joints and the rotation axes are defined on the θ-axis in the standard Rigid-FE dummies, which have an angle range from -90 to 45 degree. As the total formulation, it could cause "gimbal lock" when the lower legs fully extend ($\theta = -90$ degree). It is suggested to switch the rotation axes to the ϕ-axis.

In the neck joints, the discs are connected by four spherical joints in series. Though the axis of flexion-extension (ϕ) rotation attaches to a different disc for each joint between the two methods, as the whole neck moves, there is little difference.

Modified HIII Rigid-FE Dummy Model

To switch to the total formulation, these two cards are required,
*CONTROL_RIGID
0,1
The following changes to some generalized joint stiffness cards were suggested. To allow additional rotation for elbow and wrist joints, the generalized joint stiffness models (jsid=1, 2, 5 and 6) are modified with large stop angles (-145 and 145 degree) on the ϕ-axis. At the knees (jsid= 10 and 13), the rotation axes are changed to the ϕ-axis. In addition, in order to be able to position the lower legs in LS-PrePost, the unlocked axes for the lower legs are switched to the ϕ-axis from the θ-axis in the tree file following the keyword input deck, which is used to position the dummy in LS-PrePost. The modified cards are listed in the Appendix.

The Authors believe that these changes should have little impact to the dummy component calibration results because most joint rotation in those calibrations is dominated in a single axis. For frontal simulations, there should not be a large difference in injury measures if the dummy position remains unchanged. It might not be the case if the hip joints have unusually large initial offsets over two rotation axes.

An example model (VehicleEnvironment.TemplateWithPitchDropYawPulse.k) from LSTC was used to compare the two methods. Other than the modifications to the dummy model mentioned above, no changes were made to the input file. The dummy motions are showed in Figure 10. There is a noticeable difference in both arm kinematics during the rebound. The motions of arms from the option method seem more realistic. However there is very little difference in the injury measures such as head, chest and pelvic accelerations, upper neck forces and upper neck

moment. Their comparisons are shown in Figure 11. All acceleration channels and forces were filtered at CFC180.

Though the difference in injury measures between the two methods is insignificant in the example model provided, the modified dummy with total formulation offers more realistic dummy kinematics especially the arm motions. Because it allows the same rotation degrees of freedom as the physical dummy for the elbow and wrist joints, it also provides better dummy positioning in matching the physical test.

Dummy Positioning in LS-PrePost

When LS-PrePost Version 2.4 is used for dummy positioning, the rotation axis for the limb operations generally follows the second (Child) coordinate (namely XC, YC and ZC). Both Bryant (ZYX) angles and Euler (ZYZ) angles are reported in LS-PrePost in dummy position. The reported angles are different and somehow confusing when the rotation sequence changes. With the default method for the generalized joint stiffness, the Bryant (ZYX) angles reflect the initial joint offsets.

With the total formation, one should always follow the sequence of rotations XYZ in the current version of LS-PrePost. As an example of positioning the lower_arm, rotate x-axis first and then rotate z-axis. If rotation of the x-axis needs be modified, angle of the z-axis should be reset to zero before changing the x-axis rotation. The reported Bryant (ZYX) and Euler (ZYZ) angles should be ignored.

It is suggested to developers of LS-PrePost that the rotations for limb operation in LS-PrePost should be based on Bryant angles: rotation sequence of ZYX for the default method and XYZ for the total formulation. For example, for the total formulation, the x-rotation axis of the lower arm would always be XP on the upper arm (Parent) and the z-rotation axis would be ZC on the lower arm (Child).

Conclusion

Because of the shortcomings of the default method in the generalized joint stiffness model, the elbow and wrist joints were limited to single rotation in LSTC Hybrid III Rigid-FE dummy models. On the other hand, the total formulation option is suggested for the generalized stiffness joint model, which would allow an additional rotation degree of freedom for those joints. An example of a modified hybrid III Rigid-FE dummy model with the total formulation was provided.
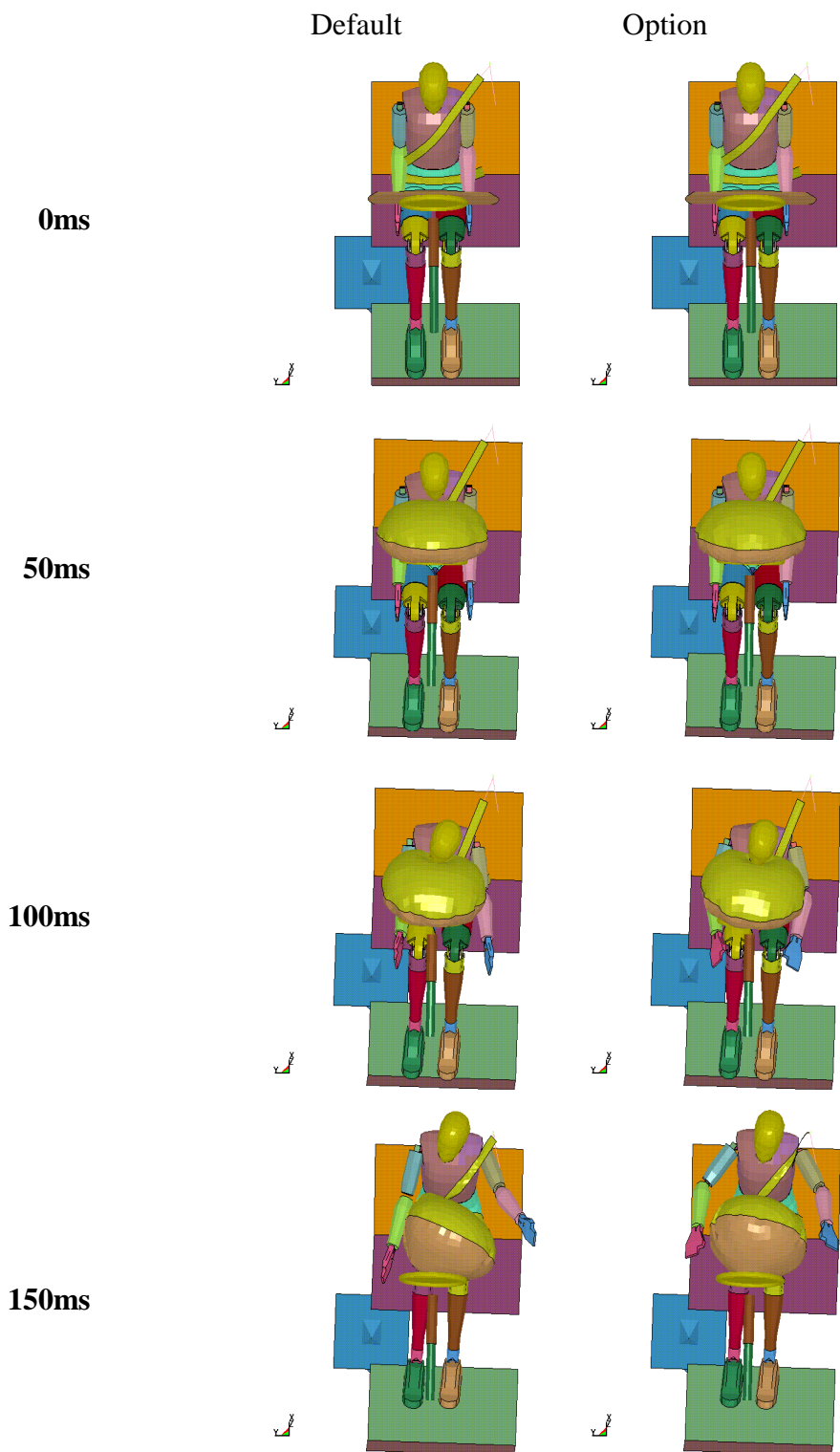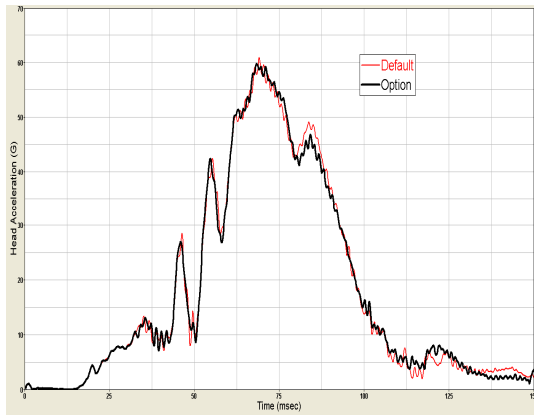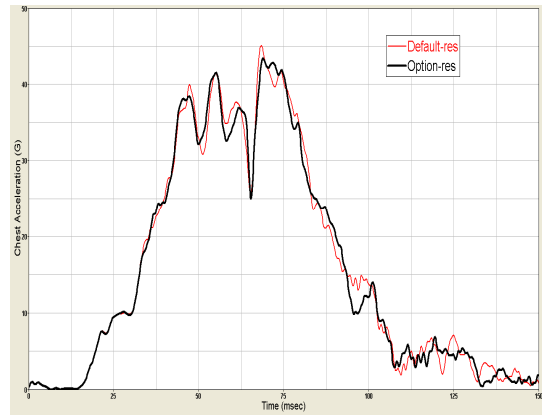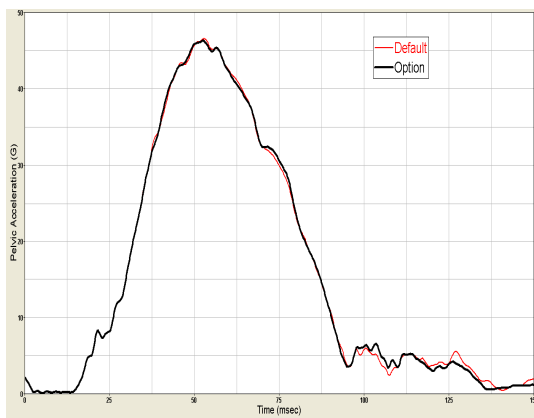
Default   Option

0ms

50ms

100ms

150ms
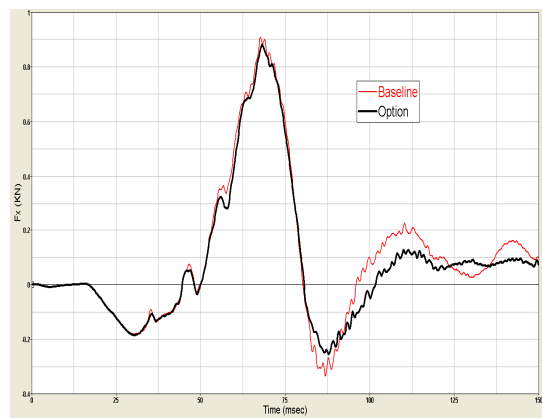
Figure 10 Comparison of dummy kinematics
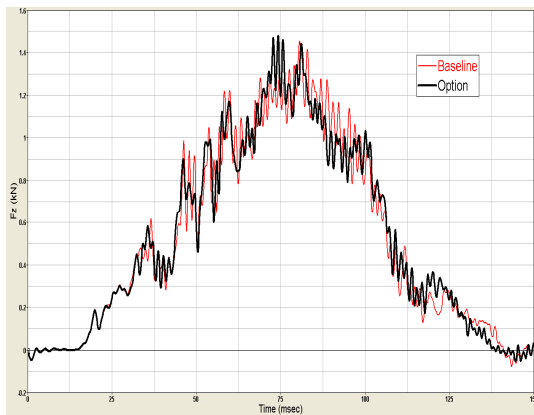
Head acceleration
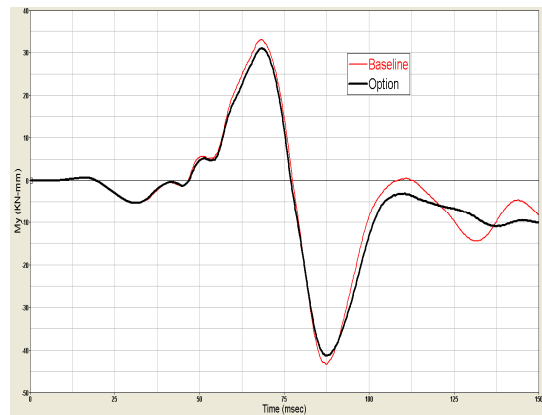
Chest acceleration

Pelvic acceleration

Fx

Fz

My

Figure 11 Comparisons of injury measures

References

1. Lars A. Fredriksson A Finite Element Data Base for Occupant Substitutes, Dissertations, LinKoping University, Sweden, 1996
2. LSTC Hybrid III Dummies Positioning & Post-Processing, Sarba Guha, Dilip Bhalsod and Jacob Krebs, LSTC, 2008
3. Stephen Kang and Paul Xiao, Comparison of Hybrid III Rigid Body Dummy Models, 10th International LS-DYNA Users Conference 2008
4. LS-INGRID: A Pre-Processor and Three-Dimensional Mesh Generator For the Programs LS-DYNA, LS-NIKE3d and TOPAZ3D Version 3.5, Livermore Software Technology Corporation, 1998
5. LS-DYNA Keyword User's Manual, Version 971, Livermore Software Technology Corporation, 2007

Appendix

```
$ add the following cards
*CONTROL_RIGID
$#      lmf      jntf    orthmd     partm    sparse    metalf
          0         1         0         0         0         0
$ change local coordinates of knee joints
*DEFINE_COORDINATE_NODES
$#      cid        n1        n2        n3      flag       dir
$        19      5971      5972      5973         0
         19      5971      5973      5972         0
*DEFINE_COORDINATE_NODES
$#      cid        n1        n2        n3      flag       dir
$        20      5974      5975      5976         0
         20      5974      5976      5975         0
*DEFINE_COORDINATE_NODES
$#      cid        n1        n2        n3      flag       dir
$        25      5989      5990      5991         0
         25      5989      5991      5990         0
*DEFINE_COORDINATE_NODES
$#      cid        n1        n2        n3      flag       dir
$        26      5992      5993      5994         0
         26      5992      5994      5993         0
$ modify stop angles on phi rotation for wrist and elbow joints
*CONSTRAINED_JOINT_STIFFNESS_GENERALIZED
$#     jsid      pida      pidb      cida      cidb       jid
          1        28        32         2         1
$#   lcidph    lcidt    lcidps    dlcidph    dlcidt   dlcidps
          0         0         0         0         6
$#     esph      fmph       est       fmt      esps      fmps
 500.00000     0.000 500.00000  0.400000 500.00000
$#    nsaph     psaph      nsat      psat     nsaps     psaps
$  0.100000 -0.100000-79.000000 30.000000  0.100000 -0.100000
 -145.0000  145.0000-79.000000 30.000000  0.100000 -0.100000
*CONSTRAINED_JOINT_STIFFNESS_GENERALIZED
$#     jsid      pida      pidb      cida      cidb       jid
          2        24        28         4         3
$#   lcidph    lcidt    lcidps    dlcidph    dlcidt   dlcidps
          0         0         3         0         5         4
$#     esph      fmph       est       fmt      esps      fmps
 500.00000  0.100000 500.00000     0.000 1800.0000  4.000000
$#    nsaph     psaph      nsat      psat     nsaps     psaps
   $  0.100000 -0.100000 -0.100000  0.100000-125.00000  0.100000
```

```
      -145.0000   145.0000 -0.100000   0.100000-125.00000   0.100000
*CONSTRAINED_JOINT_STIFFNESS_GENERALIZED
$#     jsid        pida        pidb        cida        cidb         jid
          5          30          34          10           9
$#   lcidph      lcidt      lcidps      dlcidph      dlcidt      dlcidps
          0           0           0           0           6
$#     esph        fmph         est         fmt        esps        fmps
 500.00000       0.000 500.00000   0.400000 500.00000
$#    nsaph       psaph        nsat        psat       nsaps       psaps
$   0.100000 -0.100000-30.000000 79.000000   0.100000 -0.100000
  -145.0000   145.0000-30.000000 79.000000   0.100000 -0.100000
*CONSTRAINED_JOINT_STIFFNESS_GENERALIZED
$#     jsid        pida        pidb        cida        cidb         jid
          6          26          30          12          11
$#   lcidph      lcidt      lcidps      dlcidph      dlcidt      dlcidps
          0           0          13           0           5           4
$#     esph        fmph         est         fmt        esps        fmps
 500.00000   0.100000 500.00000       0.000 1800.0000   4.000000
$#    nsaph       psaph        nsat        psat       nsaps       psaps
$   0.100000 -0.100000 -0.100000   0.100000-125.00000   0.100000
  -145.0000   145.0000 -0.100000   0.100000-125.00000   0.100000
$ modify the knee joints
*CONSTRAINED_JOINT_STIFFNESS_GENERALIZED
$#     jsid        pida        pidb        cida        cidb         jid
         10          48          50          19          20
$#   lcidph      lcidt      lcidps      dlcidph      dlcidt      dlcidps
          0           0           0           0           0           0
$#     esph        fmph         est         fmt        esps        fmps
$      0.000       0.000 1420.0000   9.033000
 1420.0000   9.033000
$#    nsaph       psaph        nsat        psat       nsaps       psaps
$      0.000       0.000-90.000000 45.000000
-90.000000 45.000000
*CONSTRAINED_JOINT_STIFFNESS_GENERALIZED
$#     jsid        pida        pidb        cida        cidb         jid
         13          49          52          25          26
$#   lcidph      lcidt      lcidps      dlcidph      dlcidt      dlcidps
          0           0           0           0           0           0
$#     esph        fmph         est         fmt        esps        fmps
$      0.000       0.000 1420.0000   9.033000
 1420.0000   9.033000
$#    nsaph       psaph        nsat        psat       nsaps       psaps
$      0.000       0.000-90.000000 45.0000000
-90.000000 45.000000
$ modify the tree file (after *END)
$ change %lock {1, 0, 1} to %lock {    0, 1, 1} for knee joints
%lower_leg_left {
        %cps {
             3854, 0
        }
        %lock {     0, 1, 1      }


%lower_leg_right {
        %cps {
             4635, 0
        }
        %lock {     0, 1, 1      }
```