

# TEST CASE DOCUMENTATION AND TESTING RESULTS

LSTC-QA-LS-DYNA-AWG-ERIF-4-16

TEST CASE ID AWG-ERIF-4

Steel Projectile Impacts Kevlar<sup>®</sup> Fabric

Tested with LS-DYNA<sup>®</sup> R11.2 Revision 26-gd2ace36

Wednesday 2<sup>nd</sup> December, 2020

**Warranty Disclaimer:**

The test case(s) described herein are for illustrative purposes only. LSTC does not warrant that a user of these or other LS-DYNA features will experience the same or similar results or that a feature will meet the user's particular requirements or operate error free. FURTHERMORE, THERE ARE NO WARRANTIES, EITHER EXPRESS OR IMPLIED, ORAL OR WRITTEN, WITH RESPECT TO THE DOCUMENTATION AND SOFTWARE DESCRIBED HEREIN INCLUDING, BUT NOT LIMITED TO ANY IMPLIED WARRANTIES (i) OF MERCHANTABILITY, OR (ii) FITNESS FOR A PARTICULAR PURPOSES, OR (iii) ARISING FROM COURSE OF PERFORMANCE OR DEALING, OR FROM USAGE OF TRADE OR. THE REMEDIES SET FORTH HEREIN ARE EXCLUSIVE AND IN LIEU OF ALL OTHER REMEDIES FOR BREACH OF WARRANTY.

| Document Information |                                                     |
|----------------------|-----------------------------------------------------|
| Confidentiality      | external use                                        |
| Document Identifier  | LSTC-QA-LS-DYNA-AWG-ERIF-4-16                       |
| Author(s)            | Prepared by LS-DYNA® Aerospace Working Group        |
| Number of pages      | 16                                                  |
| Date created         | Wednesday 2 <sup>nd</sup> December, 2020            |
| Distribution         | LS-DYNA® Aerospace Working Group / internal LSTC QA |

# Contents

|          |                                                |           |
|----------|------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                            | <b>1</b>  |
| 1.1      | Purpose of this Document . . . . .             | 1         |
| <b>2</b> | <b>Test Case Information</b>                   | <b>2</b>  |
| <b>3</b> | <b>Test Case Specification</b>                 | <b>3</b>  |
| 3.1      | Test Case Purpose . . . . .                    | 3         |
| 3.2      | Test Case Description . . . . .                | 4         |
| 3.3      | Model Description . . . . .                    | 5         |
| <b>4</b> | <b>Test Specifications</b>                     | <b>7</b>  |
| 4.1      | Test Case Targets . . . . .                    | 7         |
| 4.2      | Pass/Fail Criteria . . . . .                   | 8         |
| <b>5</b> | <b>Test Case Results</b>                       | <b>9</b>  |
| 5.1      | Software and Hardware Specifications . . . . . | 9         |
| 5.2      | Results Summary . . . . .                      | 10        |
| 5.3      | Result Details . . . . .                       | 11        |
| 5.3.1    | Sub Test Case ID 1 - Test Target 1 . . . . .   | 12        |
| 5.3.2    | Sub Test Case ID 2 - Test Target 1 . . . . .   | 13        |
| 5.3.3    | Sub Test Case ID 3 - Test Target 1 . . . . .   | 14        |
| 5.3.4    | Sub Test Case ID 4 - Test Target 1 . . . . .   | 15        |
|          | <b>References</b>                              | <b>16</b> |

# **1 Introduction**

## **1.1 Purpose of this Document**

This document specifies the test case AWG-ERIF-4. It provides general test case information like name and ID as well as information to the confidentiality, status, and classification of the test case.

A detailed description of the test case is given, the purpose of the test case is defined, and the tested features are named. The test case specifications also state the target measures for testing and the expected results, as well as their pass and fail criteria.

Testing results are provided in section 5 for the therein mentioned LS-DYNA® version and platforms.

## 2 Test Case Information

| Test Case Summary        |                                                              |
|--------------------------|--------------------------------------------------------------|
| Confidentiality          | external use                                                 |
| Test Case Name           | Steel Projectile Impacts Kevlar® Fabric                      |
| Test Case ID             | AWG-ERIF-4                                                   |
| Test Case Status         | active                                                       |
| Test Case Classification | Validation                                                   |
| Test Case Source         | Arizona State University (ASU)<br>NASA Glenn Research Center |
| Tested Keyword           | *MAT_DRY_FABRIC (ASU material model Version 1.3)             |
| Member of Test Suite     | AWG ERIF SUITE                                               |
| Metadata                 | AWG ERIF                                                     |

Table 1: Test Case Summary

### **3 Test Case Specification**

#### **3.1 Test Case Purpose**

The purpose of Test Case ID AWG-ERIF-4 is the validation of an impact experiment on layered dry fabric rings performed at NASA Glenn Research Center [4]. The reliability and consistency of LS-DYNA® as a finite element solver for this impact simulation using fabric structures is evaluated by performing analyses with different modelling approaches for the fabric (see table 4).

### 3.2 Test Case Description

This Test Case contains an impact analysis (see figure 1) using a 304L stainless steel projectile impacting 8 layers (Model LG612) <sup>1</sup> and 32 layers (Model LG969) <sup>2</sup> of dry fabric rings made from Kevlar<sup>®</sup> 49 P-Aramid.

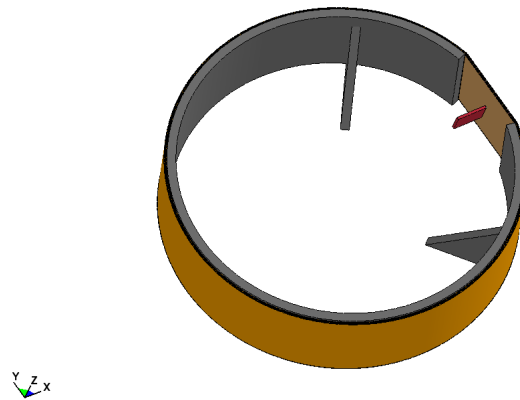


Figure 1: Model sketch: 304L stainless steel projectile impacting Kevlar<sup>®</sup> 49

Table 2 contains a short summary of the physical model set up. Details on the experimental set up can be found in [4] and [1].

| Physical Model Information  |                                                    |                                       |
|-----------------------------|----------------------------------------------------|---------------------------------------|
| Model                       | LG612                                              | LG969                                 |
| fabric geometry             | 8 layers, height = 10.0"                           | 32 layers, height = 10.0"             |
| ring geometry               | outer diameter = 40.0"                             | inner diameter = 38.0" height = 10.5" |
| ring opening                | 10.0"                                              |                                       |
| fabric material             | Kevlar <sup>®</sup> 49 P-Aramid                    |                                       |
| fabric areal density        | 0.02275 g/cm <sup>2</sup>                          |                                       |
| projectile geometry         | length = 4.0" , height = 2.0", thickness = 0.3124" |                                       |
| projectile mass             | 324 g                                              |                                       |
| projectile material         | 304L stainless steel                               |                                       |
| projectile initial velocity | 10.779 in/ms                                       | 9.252 in/ms                           |
| projectile final velocity   | 9.864 in/ms                                        | 0.00 in/ms                            |

Table 2: Model set-up data

<sup>1</sup>Model number refers to the File No, in [4]

<sup>2</sup>Model number refers to the File No, in [1]



### 3.3 Model Description

The model geometry is discretized with solid elements for the projectile and shell elements for the layers of dry fabric rings (see figure 2). The number of elements and material specifications for the model can be found in table 3.

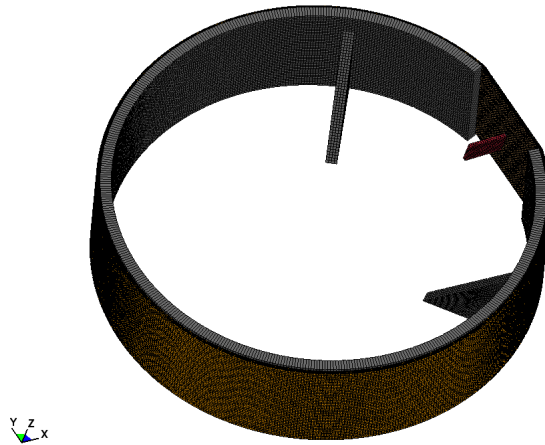


Figure 2: FEA model: 304L stainless steel projectile impacting Kevlar<sup>®</sup> 49

Two experimental set-ups are used. The two experimental set ups are named after their File No. in [4] and [1]. LG612 is an experiment where the projectile was not contained by the fabric layers. LG969 is an experiment where the projectile was contained.

Two modelling approaches for the experimental set-ups are used. The CMS (Concentric Modelling System) approach models the fabric in concentric wraps around the steel ring, whereas in the SMS (Spiral Modelling System) approach the fabric is wrapped continuously around the steel ring. The SMS approach mimics the actual test conditions.

A summary of these four sub test cases can be found in table 4.

The material definitions and their parameters can be found in the input decks.

| FEA Model information         |                                                                                                        |                     |                      |                     |
|-------------------------------|--------------------------------------------------------------------------------------------------------|---------------------|----------------------|---------------------|
| Sub Test Case ID <sup>1</sup> | 1                                                                                                      | 2                   | 3                    | 4                   |
| Model ID                      | LG612                                                                                                  | LG969               | LG612                | LG969               |
| Modelling approach            | CMS                                                                                                    | CMS                 | SMS                  | SMS                 |
| Nodes                         | 146176                                                                                                 | 217578              | 93079                | 218090              |
| Solid elements                | 81652                                                                                                  | 28442               | 28648                | 28652               |
| Solid materials               | 3                                                                                                      | 3                   | 3                    | 3                   |
| Shell elements                | 40520                                                                                                  | 162240              | 40320                | 162280              |
| Shell materials               | 4                                                                                                      | 16                  | 4                    | 16                  |
| Parts                         | 7                                                                                                      | 19                  | 7                    | 19                  |
| Number of shell layers        | 2                                                                                                      | 8                   | 2                    | 8                   |
| Fabric layers per shell       | 4                                                                                                      | 4                   | 4                    | 4                   |
| Fabric material               | *MAT_DRY_FABRIC (ASU material model Version 1.3) <sup>2</sup>                                          |                     |                      |                     |
| Ring geometry                 | outer diameter = 40.0" thickness = 1.0" height = 10.5"                                                 |                     |                      |                     |
| Fabric geometry               | height = 10.0"                                                                                         |                     |                      |                     |
| Projectile geometry           | length = 4.0" , height = 2.0" , thickness = 0.3124"                                                    |                     |                      |                     |
| Projectile velocity           | $v_x = 10.779$ in/ms                                                                                   | $v_x = 9.252$ in/ms | $v_x = 10.779$ in/ms | $v_x = 9.252$ in/ms |
| Unit system                   | in (length), ms (time), Mlbf-ms <sup>2</sup> /in (mass), Mlbf (force), Mpsi (stress), Mlbf-in (energy) |                     |                      |                     |

<sup>1</sup> Sub Test Case ID and Model ID refers to the ID's in table 4

<sup>2</sup> For details on this material see [3]

Table 3: FEA Model Information

| Sub Test Case ID | File No. <sup>1</sup> | Modelling Approach <sup>2</sup> | Input Deck Name |
|------------------|-----------------------|---------------------------------|-----------------|
| 1                | LG612                 | CMS                             | CMS.LG612.in    |
| 2                | LG969                 | CMS                             | CMS.LG969.in    |
| 3                | LG612                 | SMS                             | SMS.LG612.in    |
| 4                | LG969                 | SMS                             | SMS.LG969.in    |

<sup>1</sup> Correspond to the File No. in [4] and in [1]

<sup>2</sup> CMS (Concentric Modeling System) and SMS (Spiral Modeling System)

Table 4: Specification of sub test cases

## 4 Test Specifications

### 4.1 Test Case Targets

Table 5 displays the test case targets. The test case targets specify values or a series of values taken from the finite element analysis solution of the test case and they are used in a comparison of analysis results and experimental data. They are chosen in a way that they can be directly or indirectly compared to the experimentally determined values or observations.

| Test Case Targets |                |                |              |                    |
|-------------------|----------------|----------------|--------------|--------------------|
| Target number     | Output         | Component Type | Component Id | retrieved from     |
| 1                 | kinetic energy | part           | 11           | binout/matsum file |

Table 5: Test Case targets for Test Case ID AWG-ERIF-4

The target values are chosen to identify the kinetic energy loss of the projectile during the impact event. Target number 1 is the kinetic energy of the body of the projectile (see figure 3 for definition of the body and the cap of the projectile). The target is used to evaluate the perforation of the fabric (see section 4.2).

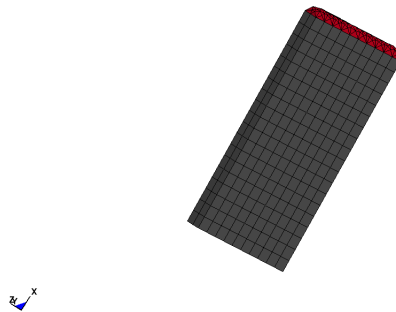


Figure 3: Part identification of the projectile: Grey coded is part 11 (body), red coded is part 12 (cap)

## 4.2 Pass/Fail Criteria

These are the Pass/Fail criteria used for the Validation of the Test Case ID AWG-ERIF-4.

The sub test case passes if the test case target data falls within the corridor bounds. Otherwise the test fails.

The test case corridors are upper and lower bounds for the test case targets. They were defined based on the test target data obtained with LS-DYNA® R9.0 Revision 108899 binaries by the following process:

- For a specific test case target, interpolate the data from different platform and executable (R9.0 Revision 108899) combinations, so that the time domain is the same.
- Calculate the upper and lower bounds by:

$$bound_{up}(i) = max(i) + 0.2 \times [max(i) - min(i)] + 0.05 \times peak$$

$$bound_{low}(i) = min(i) - 0.2 \times [max(i) - min(i)] - 0.05 \times peak$$

where  $max(i)$ ,  $min(i)$  are the maximum and minimum values at the  $i_{th}$  time step across all platforms and executable (R9.0 Revision 108899) combinations the test case was calculated with,  $peak$  is the maximum absolute y value across the whole time domain,  $bound_{up}(i)$  and  $bound_{low}(i)$  are the upper and lower bounds for the  $i_{th}$  time step.

## 5 Test Case Results

### 5.1 Software and Hardware Specifications

In order to ensure cross-platform consistency, the herein mentioned sub test cases are run on platforms specified in table 6 and the results are calculated with software versions defined in table 7.

| Platform Name | Operating system | CPU type                        | MPI-Protocol         | Number of cpu's <sup>1</sup> |
|---------------|------------------|---------------------------------|----------------------|------------------------------|
| mars          | CentOS 6.5       | Intel® Xeon® E5- 2640 @ 2.50GHz | Platform MPI 8.2.0.0 | 4                            |
| dinar3b       | SUSE LES 11      | AMD® Opteron® 6276 @ 2300MHz    | Platform MPI 8.2.0.0 | 4                            |

<sup>1</sup> Number of cpu's used for calculation of the test case

Table 6: Used Platforms and CPU Type's

| Product  | Version | Release | Revision    | Parallel type <sup>1</sup> | Precision <sup>2</sup> | executable               |
|----------|---------|---------|-------------|----------------------------|------------------------|--------------------------|
| LS-DYNA® | 971     | R11.2   | 26-gd2ace36 | SMP                        | SP                     | ls971.26-gd2ace36.R11.2  |
| LS-DYNA® | 971     | R11.2   | 26-gd2ace36 | SMP                        | DP                     | ld971.26-gd2ace36.R11.2  |
| LS-DYNA® | 971     | R11.2   | 26-gd2ace36 | MPP                        | SP                     | mpp971.26-gd2ace36.R11.2 |
| LS-DYNA® | 971     | R11.2   | 26-gd2ace36 | MPP                        | DP                     | mpd971.26-gd2ace36.R11.2 |

<sup>1</sup> MPP = Massively Parallel Processing, SMP = Symmetric Multiprocessing

<sup>2</sup> SP = single precision, DP = double precision

Table 7: Tested LS-DYNA® version

## 5.2 Results Summary

Table 8 contains the results of the Test Case ID AWG-ERIF-4 completed with all combinations of software and hardware defined in section 5.1 ( 4 \* 2 \* 4 total calculation runs).

Details on the test results can be found in the section 5.3.

The table 8 validation summary is:

- **PASS** - Pass criteria in section 4.2 is attained.
- **FAILED** - Pass criteria in section 4.2 is not attained.
- **ERROR** - sub test case terminates due to error.
- **N/A** - sub test case was not calculated.

| Sub Test Case ID | PASS/FAILED |
|------------------|-------------|
| 1                | <b>PASS</b> |
| 2                | <b>PASS</b> |
| 3                | <b>PASS</b> |
| 4                | <b>PASS</b> |

Table 8: Validation results summary for Test Case ID AWG-ERIF-4

### 5.3 Result Details

The following subsections contain detailed results for the Test Case ID AWG-ERIF-4 for LS-DYNA® R11.2 Revision 26-gd2ace36.

For each sub test case defined in section 3.3 there is a graph displaying the time history of the result target defined in section 4.1 for the platform and software version combinations defined in section 5.1.

The title of the graph states the test case ID and the name of input deck. The legend contains the result file name, output, platform, executable and number of cpu's separated by comma. A minus sign before the number of cpu's refers to the compatibility option for SMP calculations (see [2] for details on this option).

#### Example for title and legend:

##### *Title:*

'AWG\_ERIF\_TEST\_CASE\_4: CMS\_LG612.in' states the test case ID 4 and name of the input deck for sub test case 1.

##### *Legend:*

'glstat\_internal.energy,ham,ls971.26-gd2ace36.R11.2,4' states that the graph shows the internal energy derived from the 'glstat' output file for an input deck which was calculated on the 'ham' platform with a LS-DYNA® R11.2 Revision 26-gd2ace36 binary (SMP, single precision) on four processors.

### 5.3.1 Sub Test Case ID 1 - Test Target 1

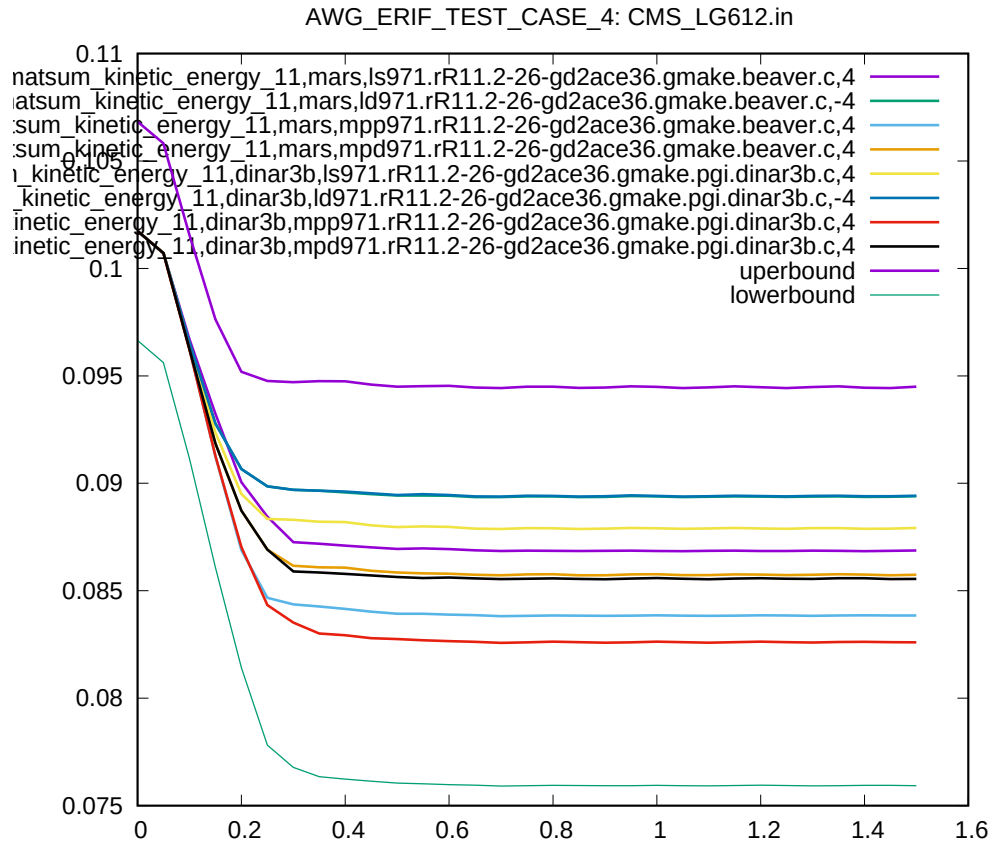


Figure 4: Cross platform results, kinetic energy part 11, sub test case ID 1



### 5.3.2 Sub Test Case ID 2 - Test Target 1

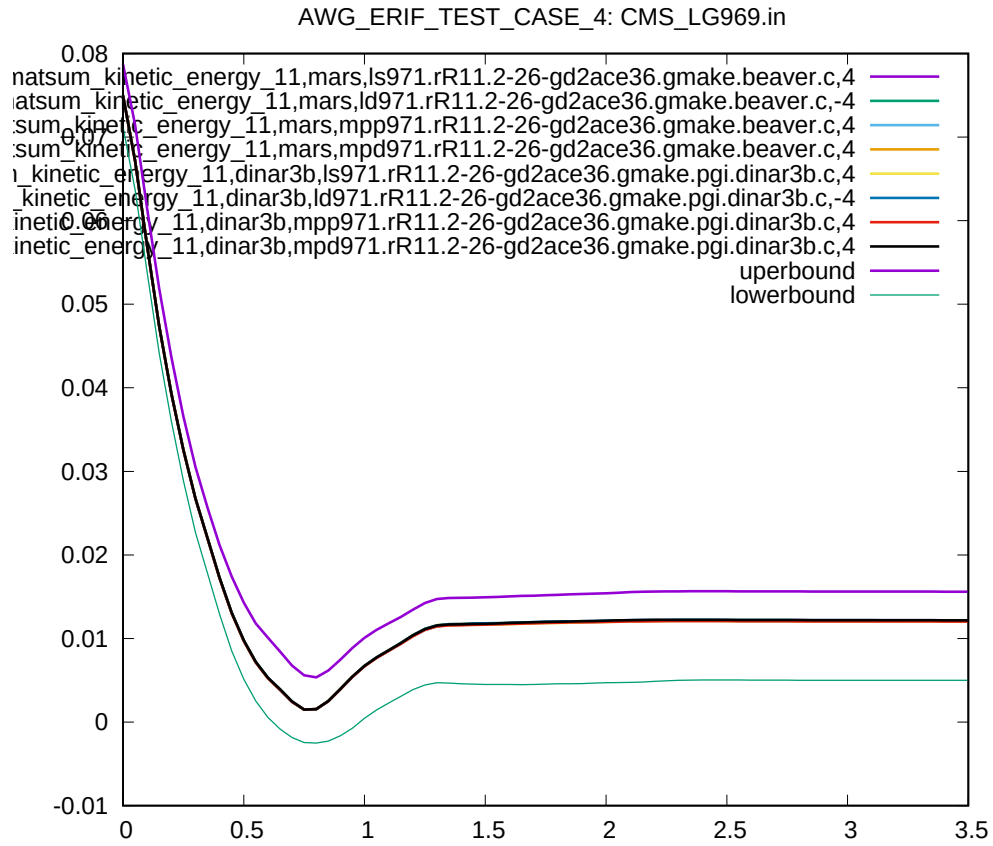


Figure 5: Cross platform results, kinetic energy part 11, sub test case ID 2

### 5.3.3 Sub Test Case ID 3 - Test Target 1

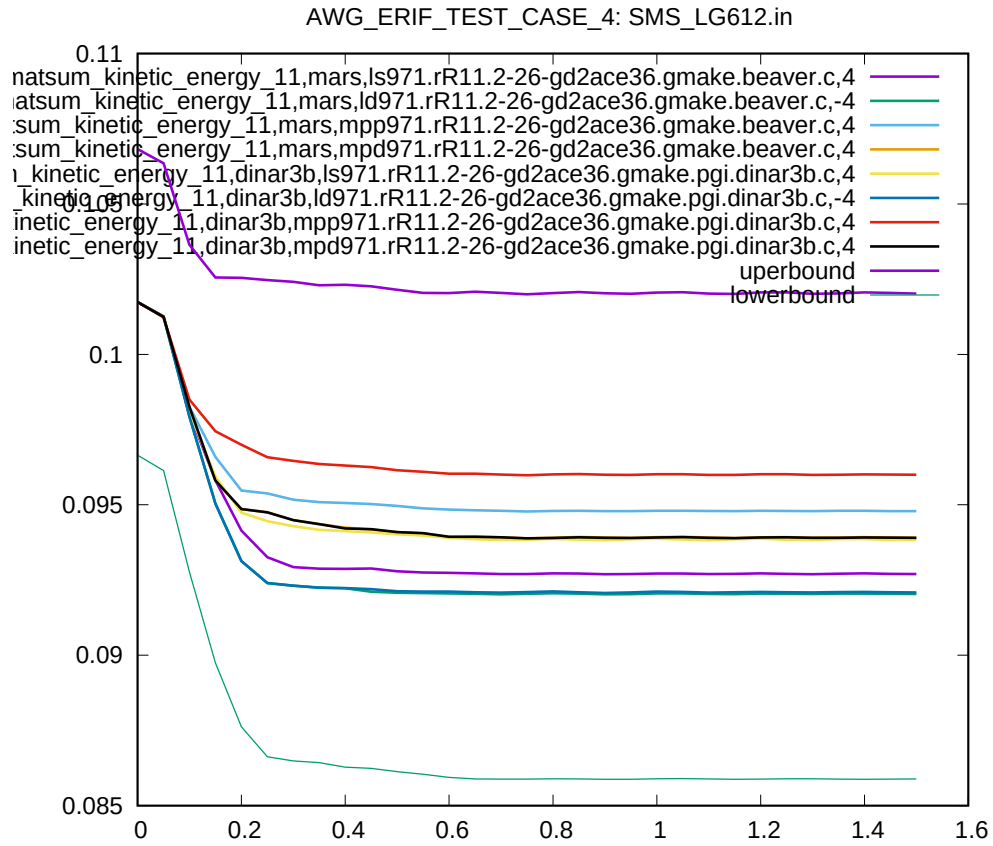


Figure 6: Cross platform results, kinetic energy part 11, sub test case ID 3

### 5.3.4 Sub Test Case ID 4 - Test Target 1

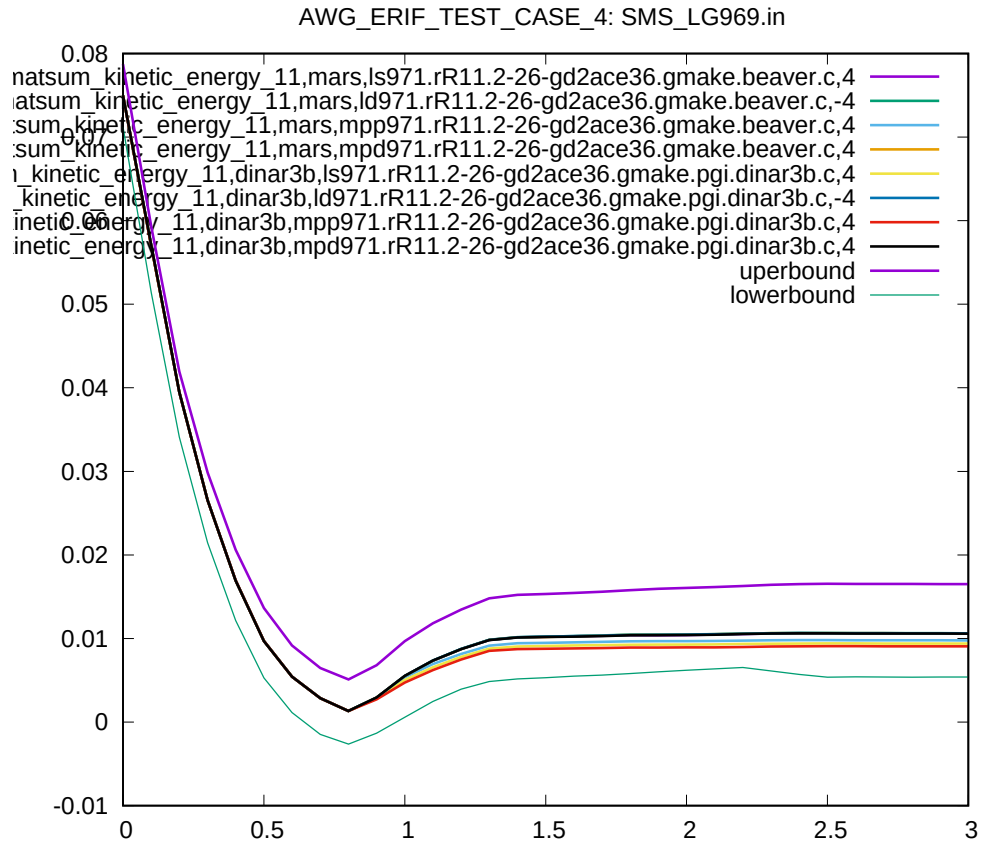


Figure 7: Cross platform results, kinetic energy part 11, sub test case ID 4

## References

- [1] *Explicit Finite Element Modeling of Multilayer Composite Fabric for Gas Turbine Engine Containment Systems, Phase III*, tech. rep., U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Research, Washington, D.C. 20591, in preparation.
- [2] LSTC, *LS-DYNA KEYWORD USER MANUAL*, 7374 Las Positas Road, Livermore, CA, 94551, USA, version 971 ed., May 2007.
- [3] S. D. RAJAN, B. MOBASHER, Z. STAHLER, S. BANSAL, D. ZHU, M. MOREA, AND K. DHANDAPANI, *Explicit Finite Element Modeling of Multilayer Composite Fabric for Gas Turbine Engine Containment Systems, Phase III Part 1: Arizona State University Material Model and Numerical Simulations*, Final Report DOT/FAA/AR-10/23,P1, U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Research, Washington, D.C. 20591, January 2011.
- [4] D. M. REVILOCK AND J. M. PEREIRA, *Explicit Finite Element Modeling of Multilayer Composite Fabric for Gas Turbine Engine Containment Systems, Phase II Part 2: Ballistic Impact Testing*, Final Report DOT/FAA/AR-08/37,P2, U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Research, Washington, D.C. 20591, February 2009.