A Resource for the State of Florida

HURRICANE LOSS REDUCTION

FOR

HOUSING IN FLORIDA:

Performance of Clay and Concrete Roof Tile

A Research Project Funded by
The State of Florida Division of Emergency Management

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ABSTRACT

Engineers have recognized that failure of the building envelope is one mechanism that can lead to severe damage of structures during hurricanes. Based on many observations following severe windstorms such as tropical cyclones, including hurricanes and typhoons, it was found that windborne debris produces nearly same amount of wind damage as direct wind loads on buildings. Hence the study of impact of wind borne debris has become one of the most extensive research areas from past few years.

There are many types of cladding materials like glass, wood, masonry. The major damage posed by a windstorm to these components is windborne debris. The issue of resistance to windborne missile impacts is addressed in ASTM E1886, ASTM E 1996. The standards for testing the impact of wind borne missile are given by Testing Application Standard (TAS) 201-94. The purpose of this project is to analyze the impact of concrete tile on cladding components using ABAQUS software, and to evaluate the strength of residential shutter materials. Parametric studies are performed with 2 inch diameter concrete roof tile in all five hurricane category wind speeds. ABAQUS is a powerful engineering simulation program, based on the finite element method. The cladding material is modeled as deformable plate and the compact wind borne debris is simulated as a rigid sphere in the program. Result show that concrete tile could indeed become wind borne debris and will damage the window if not properly protected. In addition, metal shutter should be used for protecting window damage from broken concrete tiles.

1. INTRODUCTION

Hurricanes and tornadoes constitute the primary severe windstorms that concern United States residents. These are most common in tropical weather areas one of them being State Florida. This state is affected by at least a few of these storms each year on a regular basis. In 1992, Hurricane Andrew category IV intensity on the Saffir-Simpson Scale (Simiu and Scanlan, 1996) ravaged South Florida. The devastating effect of tornado in Oklahoma City in May 1999 resulted in loss of billions of dollars and caused numerous casualties. Hurricane attacks a structure with strong, turbulent winds that continuously vary in direction. In addition, the winds pick up and carry debris that impact structures. Damage resulting from a strong hurricane impacting a populated area can be widespread

The importance of windborne debris protection to building performance in hurricanes became quite evident to experts involved in the building industry following the devastating effects of hurricane Andrew. This hurricane created an enormous amount of windborne debris, which caused substantial damage to building envelopes. These effects resulted in new requirements for design to ensure the integrity of the building envelope. One such requirement is the missile impact test or the TAS 201, where launching a wooden 2 by 4 at glazed openings, exterior walls and the roof of a building simulates the impact of windborne debris in a hurricane. This test is also extended to small missile with standard specifications, to check the resistance of window, door and impact protective systems like storm shutters for the impact of roof gravel or small portion of roof tile. To comply with the test, the building's exterior must withstand the impact of a wooden 2 by 4 striking head on, traveling at a designated velocity and cladding components such as window, door as well as impact protective systems like storm shutters must withstand the impact of small missile.

1.1 Effect of Wind borne Debris

Windborne debris has been established as a principal cause for the breaching of the building envelope during windstorms. An opening on the windward face of the building can lead to failure by allowing positive pressures to occur along with negative external pressures. Only 5% of opening on the windward wall of building is enough to allow full internal pressurization that effectively doubles the pressures acting to lift the roof and push the side wall. Based on Minor and Behr (1994) observations after hurricane Andrew (1993), glazing systems performed poorly, largely due to impact of windborne debris and damage to building contents was extensive. To preserve the integrity of the building envelope, cladding systems must be able to sustain impacts from the debris and cover openings for the duration of the storm.

Debris impacting buildings during a severe windstorm can originate from both the surrounding area and from the building. In hurricane Andrew it was observed that the failure of metal-clad buildings and mobile homes generated considerable windborne debris. Other sources of debris include roof sheathing materials, wall coverings, roof mounted mechanical equipment, parapets, garbage cans, lawn furniture, missiles originating from trees and vegetation in the area. Missiles originating from loose pavement and road gravel have also been observed in intense windstorms.

Due to complex nature of missile and debris impacts, there are no design criteria that can be used to calculate the static force of a wind missile impact. In order to determine adequate missile impact resistance for a building, the designer has to use the performance criteria of the wall, door, window, or roof section found through the missile impact test.

1.2 Objectives

The following research objectives are established to address the above stated problems:

- Identify and assess a range of wind speeds that will cause the clay and concrete roof tiles to become hazardous wind-borne debris.
- Identify and assess the effect of clay and concrete roof tiles wind-borne debris on different building components, such as other roof tiles, windows, and other vulnerable structural and non-structural components.

2. BACKGROUND

In order to assess a range of wind speed that will cause the clay and concrete roof tiles to become hazardous wind-borne debris, the aerodynamic of the clay and concrete roof tiles need to be understood. This could be performed experimentally using an air cannon similarly to the method described in TAS 201, but the problem with TAS 201 is that it does not represent the actual impact speed or the trajectory speed of the wind borne debris. In fact the TAS 201 was developed by Twisdale et al. which associate the missile impact with an estimated risk of damage. Thus, launching a 2 by 4 lumber at 35 mph does not exactly translate to the actual trajectory of wind borne debris during an event of a hurricane. Therefore, the research has to make a turn from using simple experimental air cannon test to computer simulation.

2.1 Types of Wind Borne Debris

The most primitive form of damaging debris include cladding elements such as tiles, shingles and metal sheeting and timber structural members from roofs of low-rise buildings. Other well-represented types include wall cladding and structure. Items near to ground level such as rubbish bins and letter boxes and larger items such as garden sheds, empty water tanks which can cause significant damage due to higher mass were observed in surveys. Depending on the lift-off characteristics the shapes of windborne debris are classified into three generic types: ‘compact’ (or ‘particle’) type, ‘rod’ type (including roofing members of rectangular cross section) and ‘sheet’ type. This classification can also be used for their trajectories. For this report the clay and concrete roof tiles are assume to be compact shape as they are brittle material and should break off into smaller compact shape upon impact.

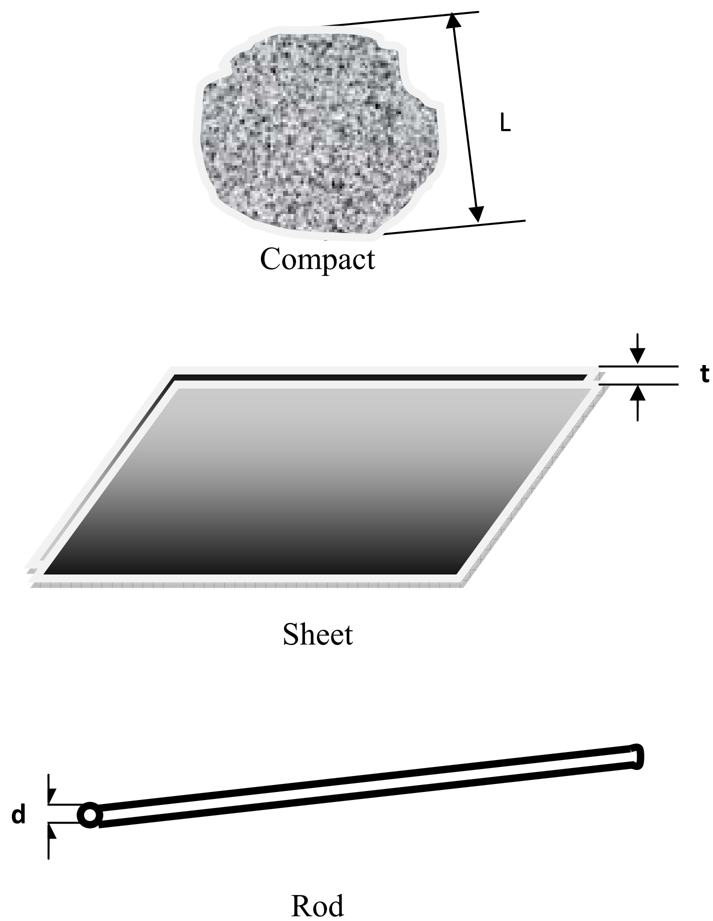

Figure 2.1 Three generic forms of windborne debris [1]

2.2 Debris Trajectories

From extensive experimental and numerical studies it was found that the three generic shapes defined above as 'compact', 'sheet' and 'rod'types can be used to define trajectories. The trajectories for compact objects are found to travel vertically towards the ground, due to gravity and vertical component of air resistance. These objects do not have aerodynamic lift forces. While in case of sheet types the lift forces are predominant and they try to keep the body in air for longer resulting in greater horizontal speed. Hence the impact on a downwind building has a greater damage potential for sheet type objects.

The horizontal velocity component of a windborne missile is given by the following function:

$$\frac{u_m}{V_s} \cong 1 - exp\left[-b\sqrt{x}\right] \text{------------ (1)}$$

Where, u_m is the horizontal missile velocity and V_s is the local (gust) wind speed.

x is the horizontal distance traveled (this can be related to average building spacing).

b is a dimensional parameter depending on the shape of the missile and its drag coefficient, and its mass; it is given by:

$$b = \sqrt{\frac{\rho_a \, C_{D,av} A}{m}} \text{-------------- (2)}$$

In Eq.(2), $C_{D,av}$ is an average drag coefficient, averaged over the rotations of the body with respect to the relative wind. For prismatic bodies, like cubes and rods with rectangular cross section $C_{D,av}$ is 0.8.The non-dimensional form of Eq. (1) for compact object is given by:

$$\bar{u} = 1 - e^{-\sqrt{2CK\bar{x}}} \quad \text{-------------- (3)}$$

Where K is a measure of the relationship between the aerodynamic force and gravity force and is called as Tachikawa number.

$$K = \frac{\rho_a U^2 A}{2mg} \qquad \text{where U is wind speed.}$$

Thus for cubes with $C_{D,av}$ = 0.8, Eq. (3) becomes $\bar{u} = 1 - e^{-\sqrt{1.6K\bar{x}}}$ -------- (4)

And for spheres with $C_{D,av}$ = 0.5, Eq. (3) becomes $\bar{u} = 1 - e^{-\sqrt{1.0K\bar{x}}}$ -------- (5)

These equations are used to simulate the clay and concrete tiles trajectories to determine the impact on cladding materials.

3. MODELLING

Abaqus is a powerful engineering simulation programs, based on the finite element method that can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations. It consists of two main analysis products, Abaqus/Standard and Abaqus/Explicit. Abaqus/Standard solves a system of equations implicitly at each solution "increment", while Abaqus/Explicit uses an explicit dynamic finite element formulation and marches a solution forward through time in small time increments without solving a coupled system of equations at each increment.

A complete Abaqus analysis usually consists of three distinct stages: preprocessing, simulation, and post processing. These three stages are linked together by files as shown below:

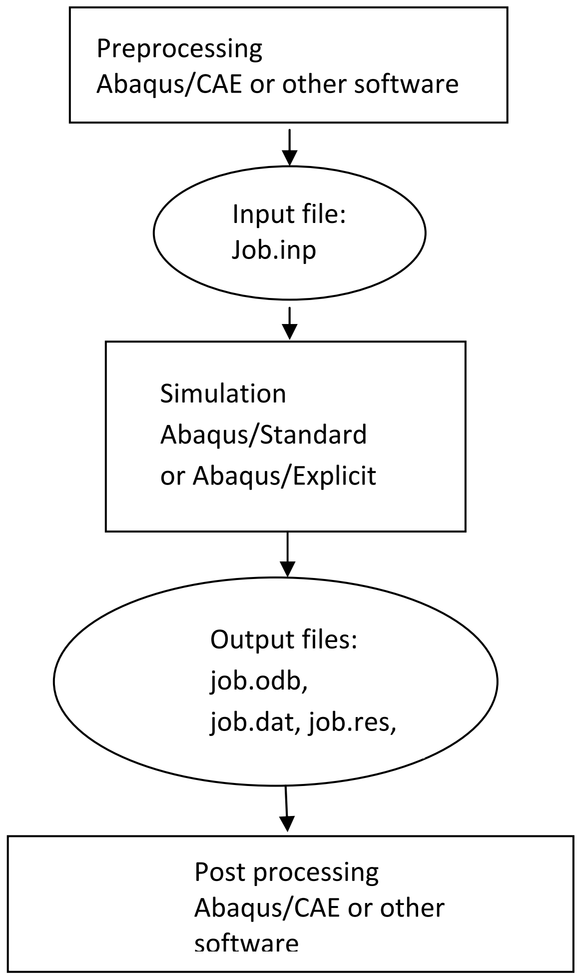

Figure 3.1 Stages of abaqus analysis [7]

Preprocessing is the stage in which the model of the physical problem is defined and an Abaqus input file. The input file can be created directly using a text editor or can be created graphically using Abaqus/CAE. Simulation is the stage in which Abaqus /Standard or Abaqus/Explicit solves the numerical problem defined in the model. Thus the output files of displacements and stresses from a stress analysis are ready for post processing. Depending on the complexity of the problem being analyzed and the power of the computer being used, it takes from seconds to days to complete analysis run. The evaluation of results is done interactively using the Visualization module of Abaqus/CAE. The visualization module has a variety of options for displaying results including color contour plots, animations, deformed shape plots, and X-Y plots.

3.1 Components of an Abaqus analysis model

The typical analysis model in Abaqus consists of discrete geometry, element section properties, material data, loads and boundary conditions, analysis type, and output requests.

- **Discrete geometry**: Basic geometry of the physical structure is modeled using finite elements and nodes. Each element in the model represents a discrete portion of the physical structure; these are connected to one another by shared nodes. The collection of all the elements and nodes in a model is called a mesh. The element type, shape, and location, as well as the overall number of elements used in the mesh affect the results obtained from a simulation. As the mesh size becomes finer, the analysis results converge to a unique solution and the analysis time increases. The extent of approximations made in the model's geometry, material behavior, boundary conditions, and loading determines how well the numerical simulation matches the physical problem.

- **Element section properties**: Abaqus has an extensive library of elements that can be used for a wide range of structural applications. The name of the element completely identifies the element family, formulation, number of nodes, and type of integration. All elements must refer to a section property definition. The section property provides any additional data required to define geometry of the element and also identifies the associated material property definition. The choice of element type has important consequences regarding accuracy and efficiency of simulation. General element families in Abaqus are shown below.

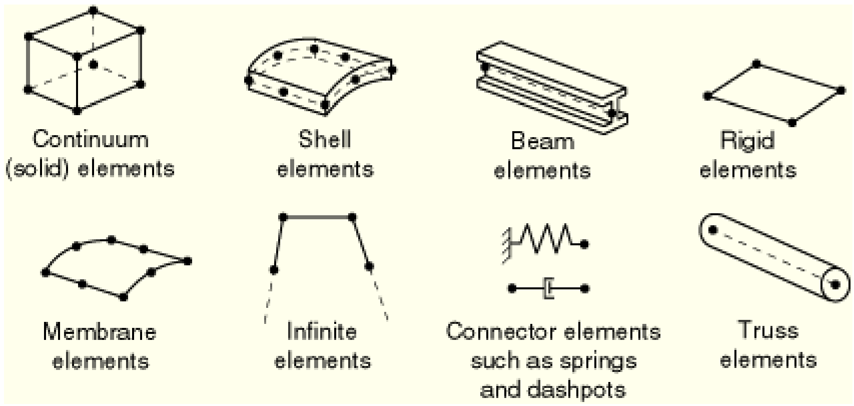

Figure 3.2 General element families [8]

- **Material data**: Material properties for all elements must be specified. For more complex material models, the validity of the Abaqus results is limited by the accuracy and extent of the material data.

- **Loads and boundary conditions**: Loads cause distortion in the physical structure thus creating stress. Most common forms of loading include:

  - point loads
  - pressure loads on surfaces
  - distributed tractions on surfaces
  - distributed edge loads and moments on shell edges
  - body forces, such as the force of gravity and
  - thermal loads

Boundary conditions are used to constrain portions of the model to remain fixed (zero displacement) or to move by a prescribed amount. In static analysis enough boundary conditions must be used to prevent the model from moving as a rigid body in any direction, otherwise unrestrained rigid body motion causes the stiffness matrix to be singular. During the solution stage a solver problem occurs that may cause simulation to stop prematurely. In dynamic analysis inertia forces prevent the model from undergoing infinite motion instantaneously as long as all separate parts in the model have some mass; hence solver problems usually indicate some other modeling problem, such as excessive plasticity.

- **Analysis type:** Abaqus can carry out many different types of simulations such as static, dynamic, seismic, quasi-static etc. In a static analysis long-term response of the structure to the applied loads is obtained. In other cases the dynamic response of a structure to the loads may be of interest: for example, the effect of a sudden load on a component, such as occurs during an impact, or the response of a building in an earthquake.

- **Output requests:** An Abaqus simulation can generate a large amount of output. To avoid using excessive disk space, you can limit the output to that required for interpreting the results.

3.2 Simulation Description for Impact Analysis

This simulation of rigid projectile impacting eroding plate has two components rigid spherical projectile that represents compact wind borne debris like roof gravel or roof tile and a flat plate that represents any cladding material.

3.2.1 Plate

The plate is assumed to be semi-infinite in size compared to the projectile. This is accomplished by using CIN3D8 infinite elements around the perimeter of the plate. C3D8R elements were used to define the impact surface of the pate. These are 8-node linear brick, reduced integration continuum elements. Reduced integration elements use one fewer integration point in each direction than the fully integrated elements. Reduced integration, linear elements have just a single integration point located at the element's centroid. These solid continuum elements in Abaqus can be used for linear analysis and for complex nonlinear analyses involving contact, plasticity and large deformations.

The user can specify properties for any kind of material of the plate, for example the properties for steel include Young's modulus, plastic range, poisson's ratio, density, and shear failure which causes Abaqus/Explicit to remove elements from the mesh as they fail. Failure is assumed to occur at an equivalent plastic strain of 100%, at that point the element is removed from the model instantaneously. These material properties are defined separately for different types of elements. Only half of the plate is modeled, using appropriate symmetry boundary conditions in the x-z plane. In order to select second-order accurate formulation for solid continuum elements, to activate distortion control for solid elements, to specify whether elements must be deleted when they are completely damaged, or to specify a value of the scalar degradation parameter certain section control options like hour glassing and centroid kinematic formulation were used in the simulation.

3.2.2 Rigid body

In Abaqus a rigid body is a collection of nodes and elements whose motion is governed by the motion of a single node, known as rigid body reference node. The shape of rigid body does not change during a simulation but can undergo large rigid body motions. In this simulation the rigid body is defined in the shape of a sphere with specific diameter and mass corresponding to a uniform material density. The rotary inertia of the sphere is not needed in the model because it is assumed that there is no friction between the sphere and the plate. Boundary conditions are applied to constrain the motion of the sphere in the y-direction. The impact of rigid body at oblique angles and at different velocities is specified at the reference node. A rigid body reference node has both translational and rotational degrees of freedom.

There are two approaches for modeling the surface of a sphere, using analytical rigid surface and using R3D4 rigid elements. In this simulation, R3D4 (Rigid three dimensional quadrilateral) elements are used for modeling analytical rigid surface of the sphere. However, more complex three-dimensional surface geometries that occur in practice must be modeled with surfaces formed by element faces.

3.2.3 Contact surface

The contact of the surface of the rigid sphere is modeled as an element-based surface. Since elements in the plate will fail and be removed from the model, nodes in the interior of the plate will be exposed to contact with the surface of the rigid sphere. A node-based surface that contains all of the nodes in the plate within a radius of the sphere of point of impact is defined with *SURFACE, TYPE=NODE option. And a contact pair option is used to define contact between the surface of the sphere and node-based surface of the plate.

3.2.4 Explicit dynamic analysis

This option in Abaqus performs a large number of small time increments efficiently. The explicit central-difference operator satisfies the dynamic equilibrium equations at the beginning of the increment; the accelerations calculated at time t are used to advance the velocity solution to time $t+\Delta t/2$ and the displacement solution to time $t+\Delta t$. The user can define the overall step time in dynamic analysis but the time increment depends on the number of materials used in the model, if the model contains only one material type, the initial time increment is directly proportional to the size of the smallest element in the mesh. If the mesh contains uniform size elements but contains multiple material descriptions, the element with the highest wave speed will determine the initial time increment.

Since infinite elements were used in the model, Abaqus/Explicit uses Element-by-Element estimation. This element-by-element estimate is determined using current dilatational wave speed in each element. This is a conservative estimate compared to global stability estimate; it will give a smaller stable time increment than the true stability limit that is based upon the maximum frequency of the entire model. The concept of the stable time increment as the time required to propagate a dilatational wave across the smallest element dimension is useful for interpreting how the explicit procedure chooses the time increment during analysis.

3.2.5 Output

In Abaqus/Explicit output can be requested for output to the results (.fil) file or as either field- or history type output to the output database (.odb) file. For components of stress, strain, and similar material variables, 1, 2, 3 refer to global directions for solid elements. For nodal variables, 1, 2, 3 refer to global directions (1-X, 2=Y, 3=Z except for axisymmetric elements, in which case 1=R, 2=Z). Output of the principal values can be requested for stresses, logarithmic strains, and nominal strains. Either all principal values or the minimum, intermediate, or maximum values can be obtained.

History output for impact simulation can be obtained for velocity of the missile, kinetic energy of the model, Internal energy of whole model, plastic dissipation, external work for whole model, total energy etc.

Deformed shapes at different stages of the analysis are shown in figures below:

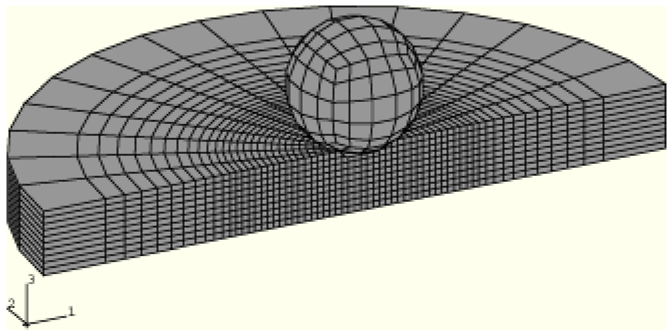

Figure 3.3 formed shape [8]

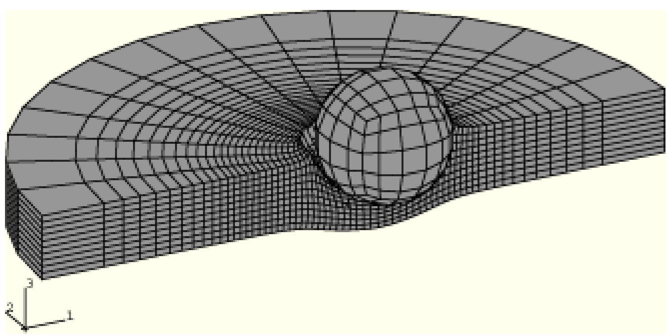

Figure 3.4 Deformed shape at 10 microseconds (analysis using the centroid kinematic and combined hourglass section control options) [8]

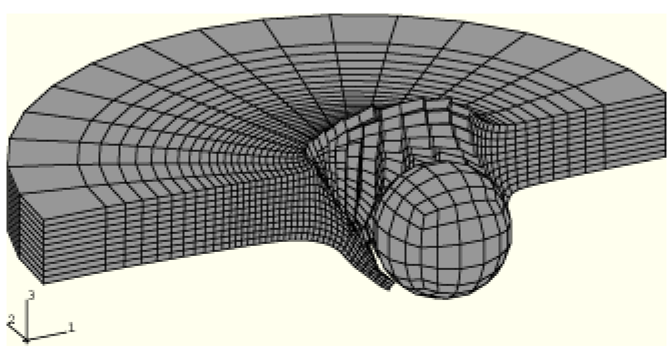

Figure 3.5 Deformed shape at 30 microseconds (analysis using the centroid kinematic and combined hourglass section control options) [8]

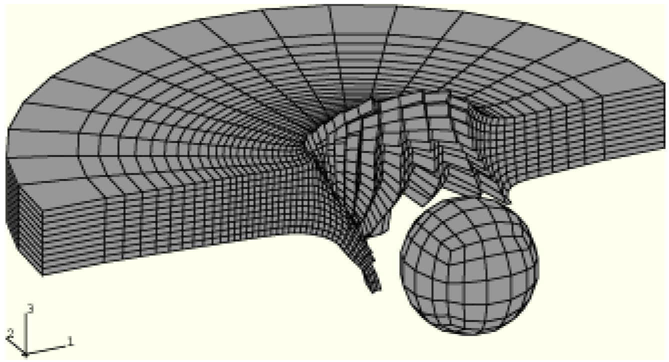

Figure 3.6 Deformed shape at 40 microseconds (analysis using the centroid kinematic and combined hourglass section control options) [8]

3.2.6 Methodology

In this analysis cladding component is represented by a deformable plate and for simplicity compact wind-borne debris is represented by a rigid body. Because of this assumption, unrealistic variations in kinetic energy were observed as shown in figure 3.8 below. There is certain increase in kinetic energy after some dissipation which cannot be true in any impact problem. Hence the time step used in this study was restricted to the first increase in kinetic energy. For example the time step in the beginning was 0.4x10E-3 seconds as shown in figure 3.8 below. It is reduced to around 0.025x10E-3 seconds, the time step at the first rise in kinetic energy.

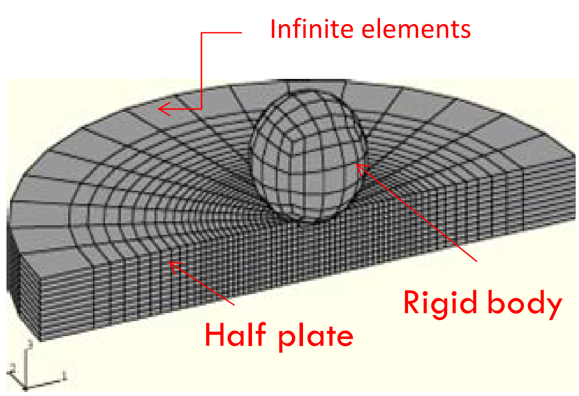

Figure 3.7 Components of model

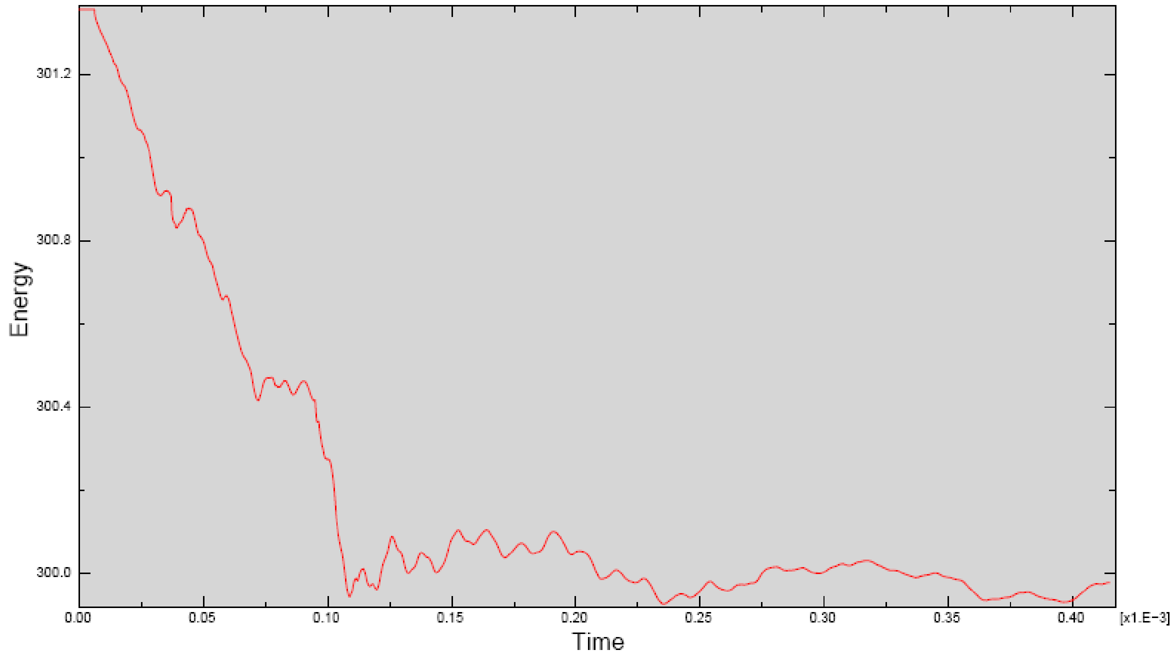

Figure 3.8 Graph for Kinetic Energy

3.2.7 Model Calibration

This model is calibrated for impact of 5gram steel ball on 6mm thick glass, for impact of 6kg concrete debris on 1¼ inch thick masonry and for impact of 6kg concrete debris on 12mm thick wood. The resulting impact kinetic energies are verified with the experimental values of McDonald and Minor given in table 3 [1].The results of calibration for each material are discussed in detail below.

Table 3.1 Material properties for cladding components

Material Properties	Glass[1]		Aluminium[2]	Masonry[3]	Wood[3]	Steel[3]
	Fully tempered	Heat Strengthened				
Youngs Modulus (N/m^2)	8.27E+07	2.07E+08	69E+09	6.21E+09	1.08E+10	206.8E+09
Yield Stress (N/m^2)	1.38E+08	N/A	213.7E+06	8.79E+06	5.00E+07	1220E+06
Density (Kg/m^3)	2.5E+03	2.5E+03	2712.63	240.2769	560	7800
Thickness (m)	0.0025	0.0025	0.0013	0.0317	0.012	0.0007

Notes:

1. Source: www.efunda.com and Madan Mehta, Walter Scarborough, Diane Armpriest, "Building construction principles, material and systems" Pearson Prentice Hall.
2. Source: Ronald A. Wash, Denis cormier, "Machining and Metalworking Handbook", third edition,McGraw-Hill.
3. Source: Robert R. Schneider, Walter L. Dickey, "Reinforced Masonry Design", third edition.
4. Source: David W. Green, Jerrold E. Winandy, and David E. Kretschmann, Wood Handbook-Chapter 4- Mechanical Properties of Wood.
5. Source: Ronald A. Wash, Denis cormier, "Machining and Metalworking Handbook", third edition, McGraw-Hill.

Table 3.2 Threshold of kinetic energy for failure of common wall materials [1]

Material	Perforation velocity (m/s)	Impact velocity (m/s)	Impact Kinetic Energy (Joules)
12mm thick plywood	23.2	N/A	1620
unreinforced concrete masonry	12	N/A	2160
fully tempered glass	N/A	20	1

3.2.7.1 *Glass*

The contour plot for the impact of 5gram steel ball with a velocity of 20m/s and the range of nodal displacement values are as shown in figure 3.9 below. The kinetic energy for the impact of 5gram steel ball on 6mm thick fully tempered glass plate from analysis was found to be 1 joule which is same as that obtained in the experimental tests by Minor [1]. The corresponding graph for kinetic energy is shown in appendix A.

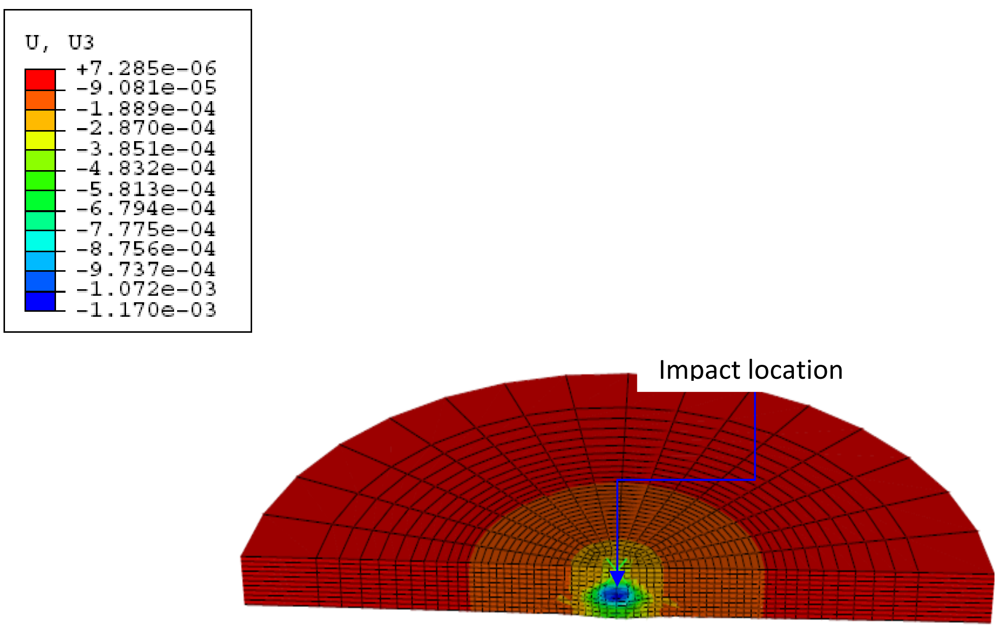

Figure 3.9 Impact of 5gm steel ball on 6mm thick fully tempered glass

3.2.7.2 Wood

The contour plot for the impact of 6kg concrete debris and the range of nodal displacement values are as shown in figure 3.10 below. The kinetic energy for the impact of 6kg concrete debris on 12mm thick plywood from analysis was found to be 1615 joules while the value from McDonald [1] experimental tests was 1620 joules. There was a very small percentage of error (0.3%) in the value obtained from analysis. The corresponding graph for kinetic energy is shown in appendix A.

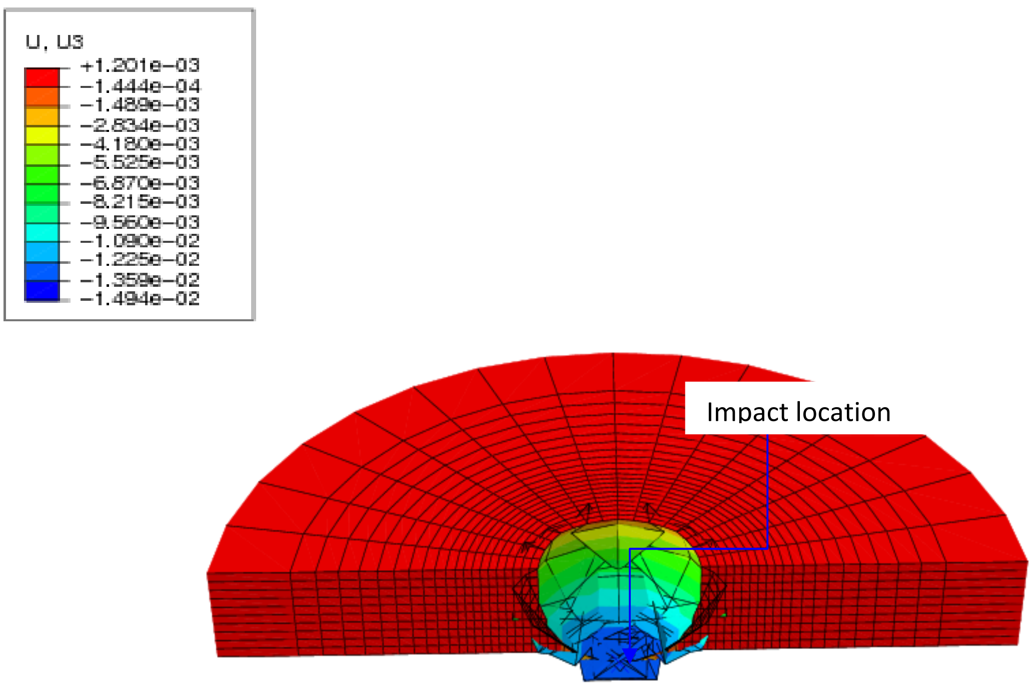

Figure 3.10 Impact of 6kg concrete debris on 12mm thick wood

3.2.7.3 Masonry

The contour plot for the impact of 6kg concrete debris and the range of nodal displacement values are as shown in figure 3.11 below. The kinetic energy for the impact of 6kg concrete debris on 1¼ inch thick masonry from analysis was found to be 2155 joules while the value from McDonald [1] experimental tests was 2160 joules. There was a very small percentage of error (0.3%) in the value obtained from analysis. The corresponding graph for kinetic energy is shown in appendix A.

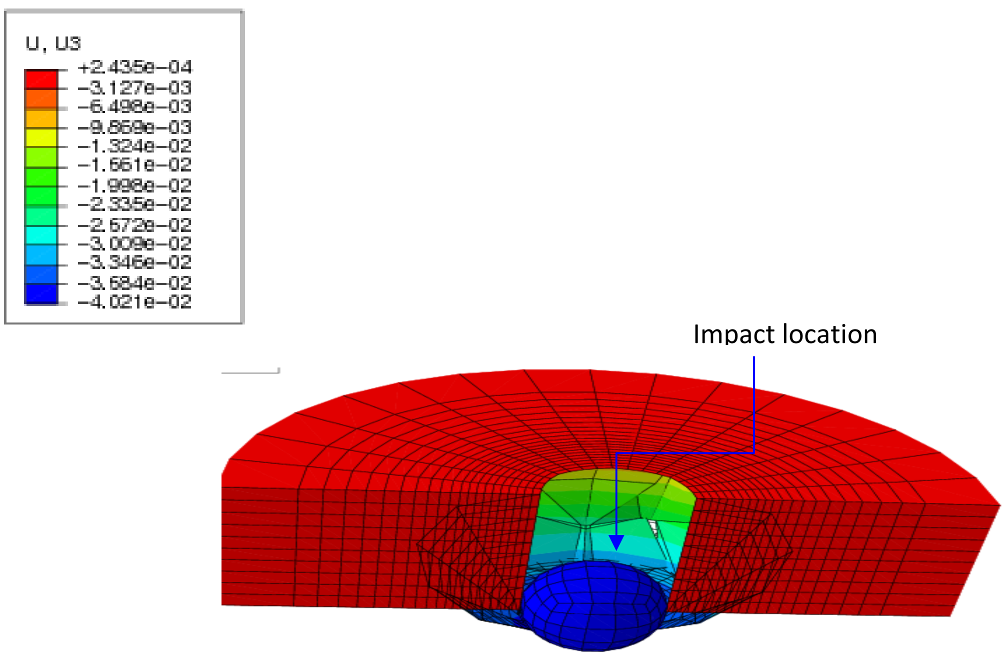

Figure 3.11 Impact of 6kg concrete debris on 1¼ inch thick masonry

4. PARAMETRIC STUDIES

In Abaqus different material properties such as brittle and ductile properties can be defined using separate commands. For brittle materials commands like *Brittle cracking, *Brittle failure

*Brittle shear were used in which remaining direct stress after cracking, direct cracking strain are defined. In case of ductile materials like steel and aluminum, material properties are defined using commands like *Elastic, *Plastic in which values of yield stress, plastic strain are defined.

To evaluate the strength of existing residential shutter materials parametric studies were performed with different cladding materials like steel, aluminum, glass, wood, masonry at five hurricane category wind speeds. The thickness of steel, aluminum and wood are based on the standard shutter thickness. For masonry, the thickness is based on standard brick thickness, for glass these are based on some of the nominal thicknesses used for window component. The concrete debris of 0.051m (2 in.) that represents a piece of roof tile was used in the analysis.

4.1 Glass

In case of 2mm, 4mm and 6mm thick glass, failure was observed due to impact of 2 inch diameter debris for category 1 wind speed. Hence it was concluded that glass is not safe in any other categories including category one. All windows of building needs to be protected from damage due to impact, otherwise it would eventually lead to the increase in internal pressure that causes complete damage of the building. The results of analysis are shown in table 4.1 below. The contour plots for three glass thicknesses and the range of nodal displacements are shown in figures 4.1, 4.2 and 4.3 below. The corresponding graphs for kinetic energy are shown in appendix B.

Table 4.1 Analysis results for impact of debris on glass

Glass	Hurricane category	Debris velocity (m/sec)	Analysis result
2mm thick	1	42.47	glass failed
4mm thick			
6mm thick			

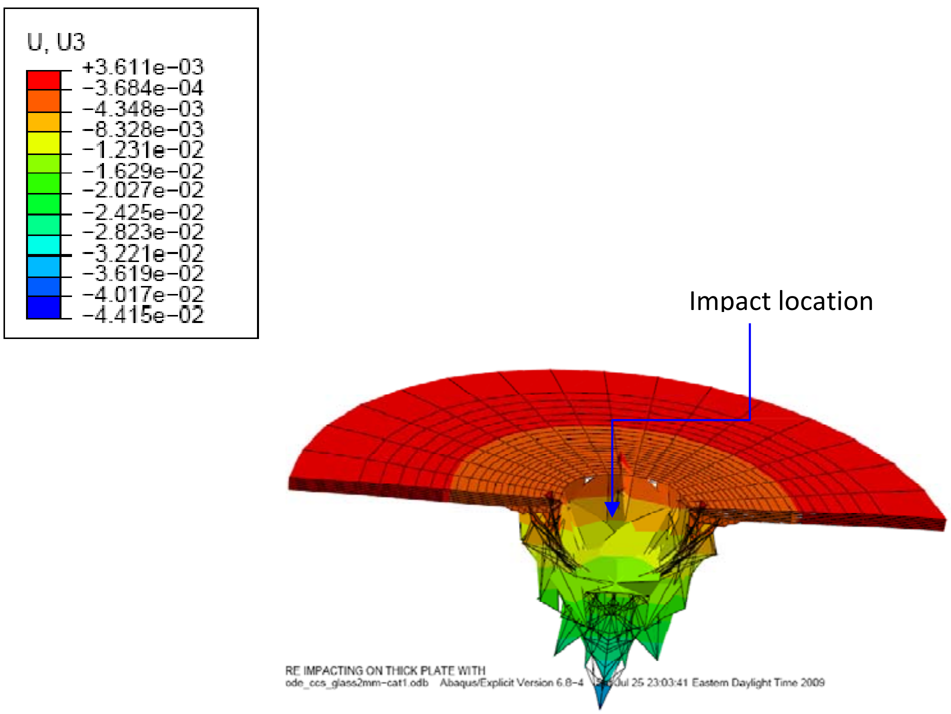

Figure 4.1 Category 1 impact of debris on 2mm thick glass

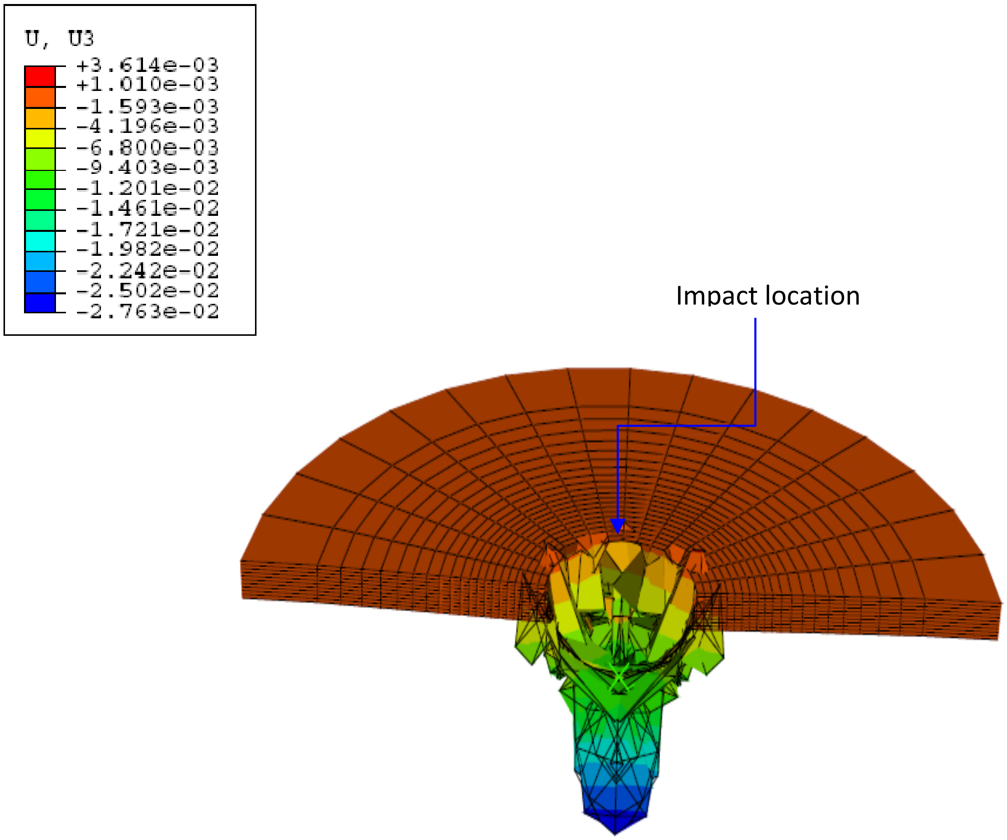

Figure 4.2 category 1 impact of debris on 4mm thick glass

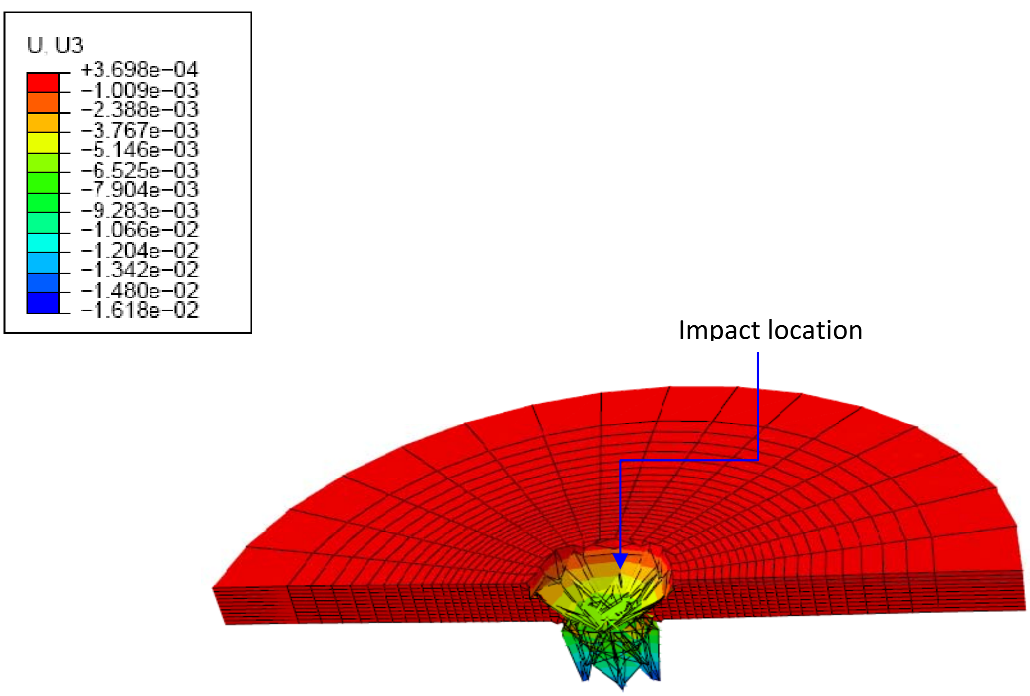

Figure 4.3 category 1 impact of debris on 6mm thick glass

4.2 Wood

In the analysis of impact of 2inch diameter concrete debris on 12mm thick plywood, there was indentation in categories 1 &2 and from category 3and above there was a failure. Hence this material is safe only for lower categories 1 & 2 for categories 3 and above it leads to increase in the internal pressure that causes complete damage of the building. The results of analysis are shown in table 4.2 below. The contour plots for categories 1 and 3 are shown in figures 4.4 and 4.5 below. The intensity of impact was measured from the nodal displacement values The corresponding graphs for kinetic energy are shown in appendix B. The reason for using 12 mm thick plywood instead of the thicker 15 mm plywood is because 12 mm plywood are more readily available at local supply store and tends to be cheaper than 15 mm plywood. Unlike metal shutter the installation of plywood on window are performed by consumer and will have some construction problem.

Table 4.2 Analysis results for impact of debris on wood

Cladding Material	Hurricane category	Debris velocity (m/sec)	Analysis result
Wood	1	42.47	indentation of 0.0085 m
	2	49.17	indentation of 0.0098 m
	3	58.11	failed
	4	62.58	failed
	5	67.06	failed

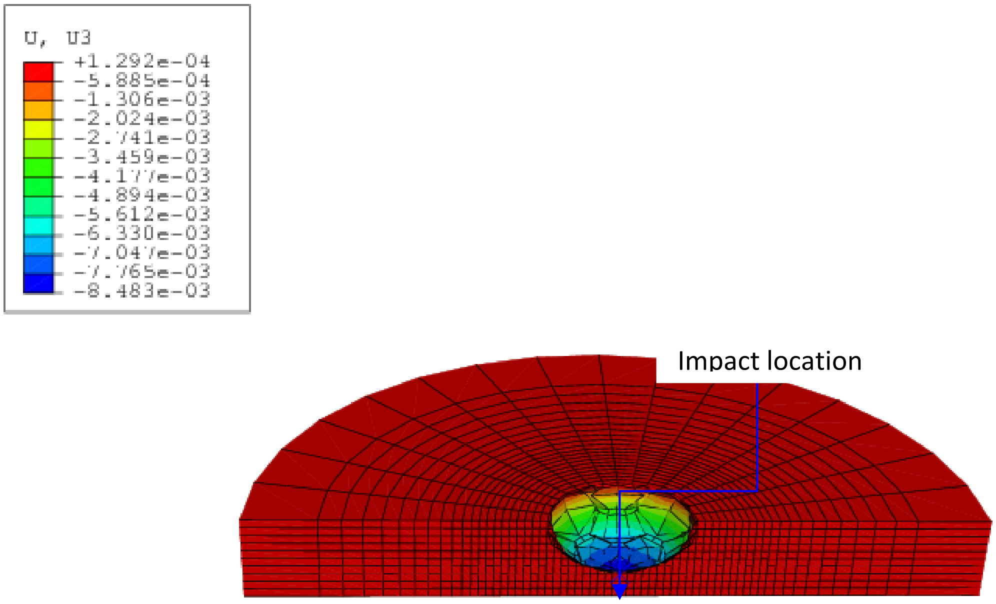

Figure 4.4 category 1 impact of debris on wood

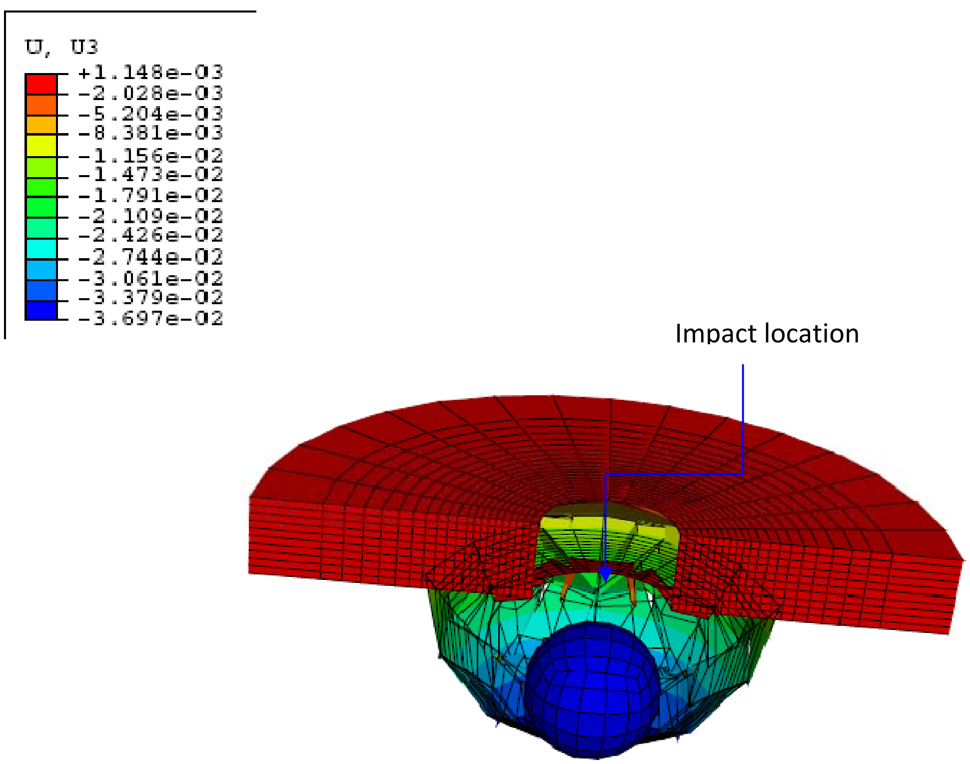

Figure 4.5 category 3 impact of debris on wood

4.3 Steel

In the analysis of 2 inch diameter concrete debris on 0.607mm thick steel (the same thickness used in steel shutter), there was deflection in all five category wind speeds, the values of deflection increased with increase in velocity as shown in table 4.3 below. However the stress values were found to be in the elastic range for all the five categories, which signifies a temporary deformation. Due to the provision of some clearance distance between shutter material and glass window, this deflection may not result in damage of the glass that creates internal pressure in the building. Thus the overall safety of the building can be achieved. The contour plots for category 1 and category 5 are shown in figures 4.6 and 4.7 below. The ranges of nodal displacement values used for measuring deflection are as shown in figures 4.6 and 4.7 below. The corresponding graphs for kinetic energy for category 1 and category 5 are shown in appendix B.

Table 4.3 Analysis results for impact of debris on steel

Cladding Material	Hurricane category	Debris velocity (m/sec)	Analysis result
Steel	1	42.47	deflection of 0.0029 m
	2	49.17	deflection of 0.0034 m
	3	58.11	deflection of 0.0041 m
	4	62.58	deflection of 0.0044 m
	5	67.06	deflection of 0.0047 m

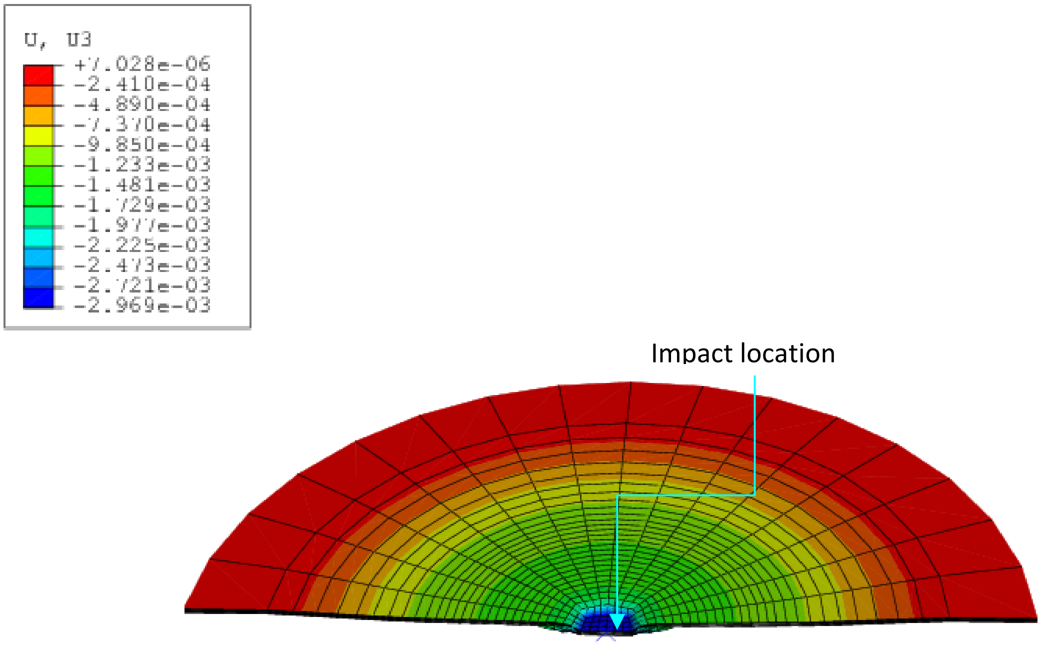

Figure 4.6 category 1 impact of debris on steel

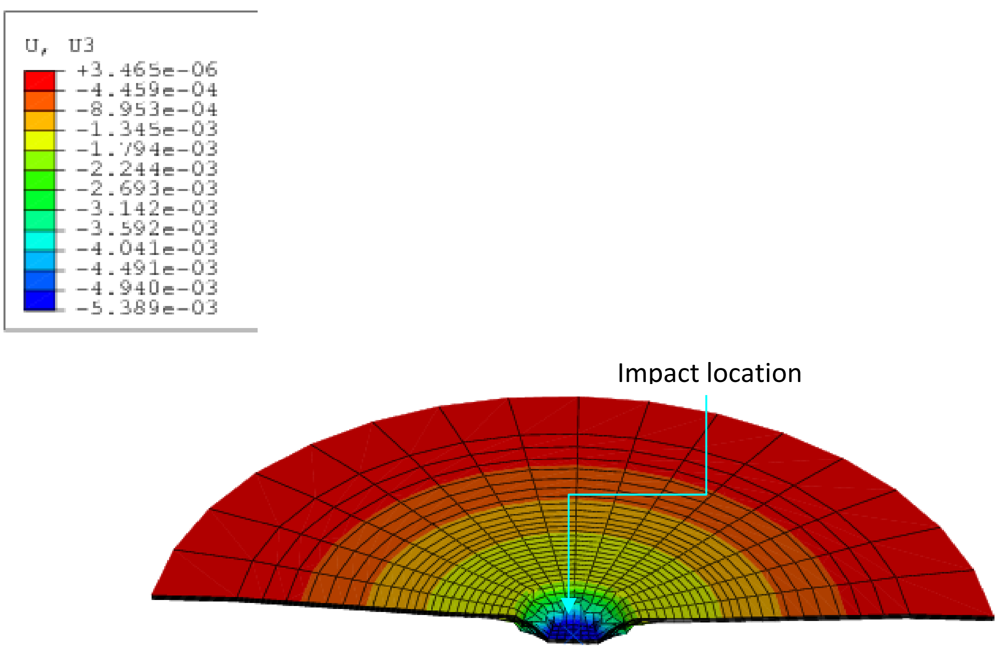

Figure 4.7 category 5 impact of debris on steel

4.4 Aluminum

In the analysis of impact of 2 inch diameter concrete debris on 1.27 mm thick aluminum (the same thickness used in aluminum shutter), similar deflection results as that of steel were observed. But these deflection values were higher compared to steel. The stress values for all five category wind speeds were found to be in the elastic range, hence similar result is interpreted for aluminum. It is a safe shutter material for all five category wind speeds. The contour plots along with the range of nodal displacement values for category 1 and category 5 are shown in figures 4.8 and 4.9 below. The graphs for kinetic energy for all five category wind speeds are shown in appendix B.

Table 4.4 Analysis results for impact of debris on aluminum

Cladding Material	Hurricane category	Debris velocity (m/sec)	Analysis result
Aluminum	1	42.47	deflection of 0.0059 m
	2	49.17	deflection of 0.0069 m
	3	58.11	deflection of 0.0081 m
	4	62.58	deflection of 0.0087 m
	5	67.06	deflection of 0.0094 m

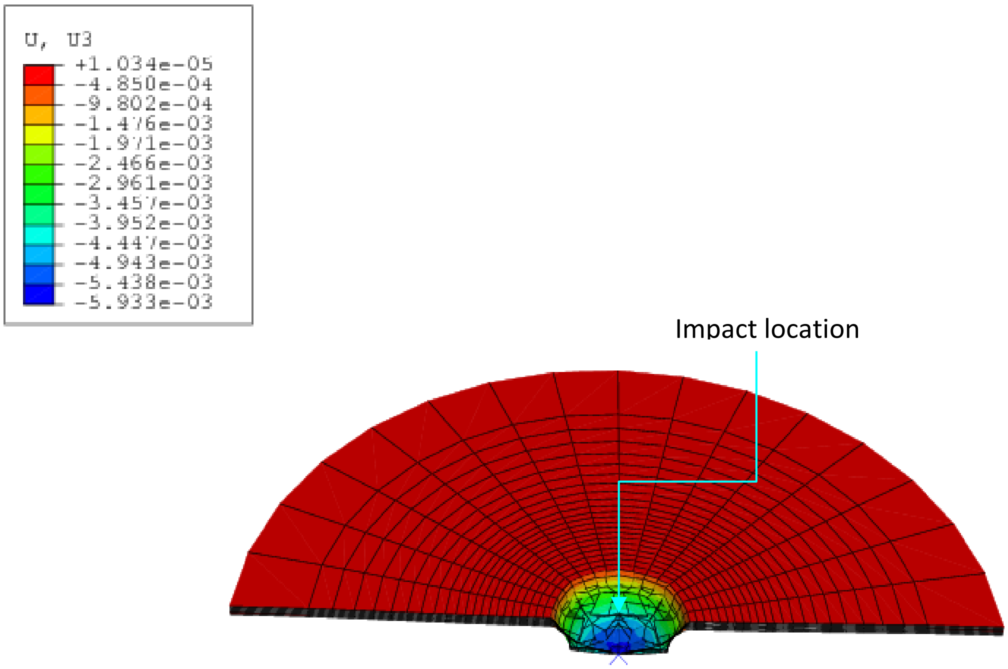

Figure 4.8 category 1 impact of debris on aluminum

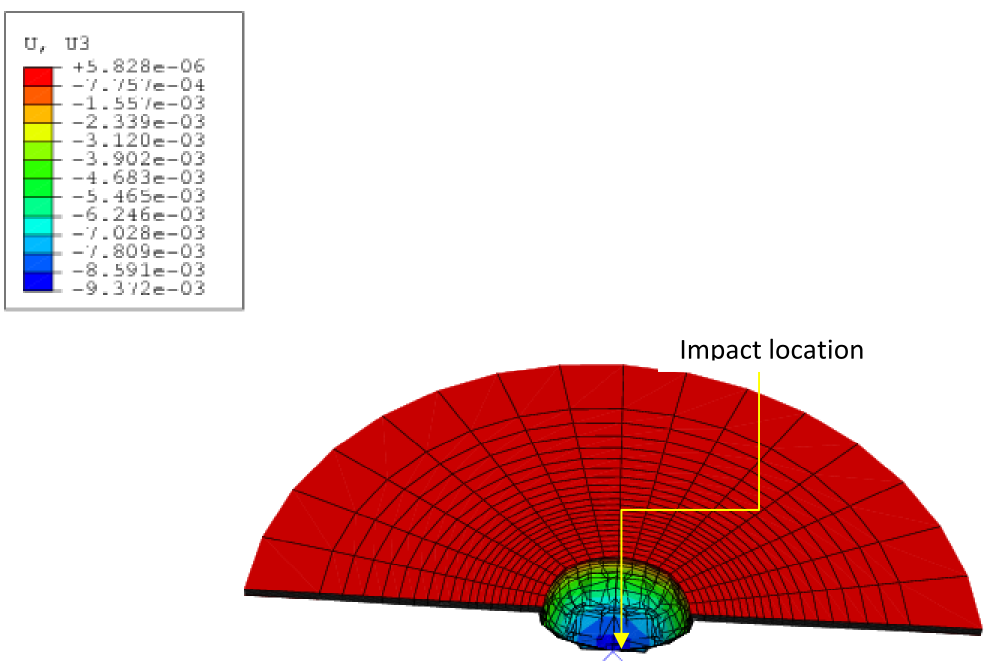

Figure 4.9 category 5 impact of debris on aluminum

4.5 Masonry

In the analysis of impact of 2 inch diameter concrete debris on 1¼ inch thick masonry (this represent the thickness of the solid section), indentation was observed at the location of impact in all five category wind speeds. The values of indentation are shown in table 4.5 below. These values are not significant; hence the damage on the outer shell of the building is negligible and can be repaired by patch work. This does not pose any threat to the internal pressure or to the failure of building envelope. The contour plots for category 1 and category 5 along with the range of nodal displacement values are shown in figures 4.10 and 4.11 below. The corresponding graphs for kinetic energy are shown in appendix B.

Table 4.5 Analysis results for impact of debris on masonry

Cladding Material	Hurricane category	Debris velocity (m/sec)	Analysis result
Masonry	1	42.47	indentation of 0.0042 m
	2	49.17	indentation of 0.0049 m
	3	58.11	indentation of 0.0058 m
	4	62.58	indentation of 0.0063 m
	5	67.06	indentation of 0.0067 m

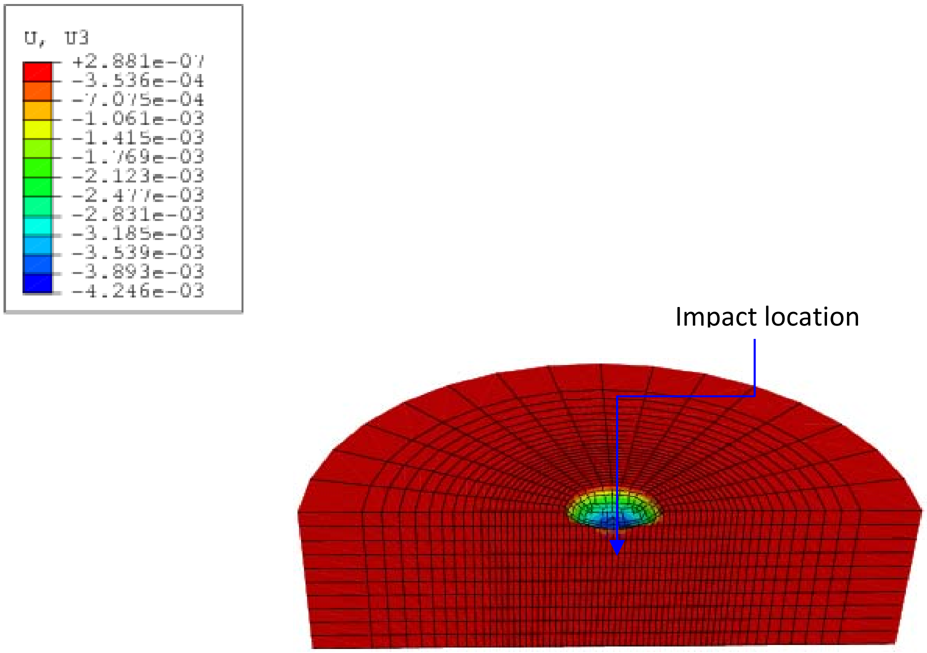

Figure 4.10 category 1 impact of debris on masonry

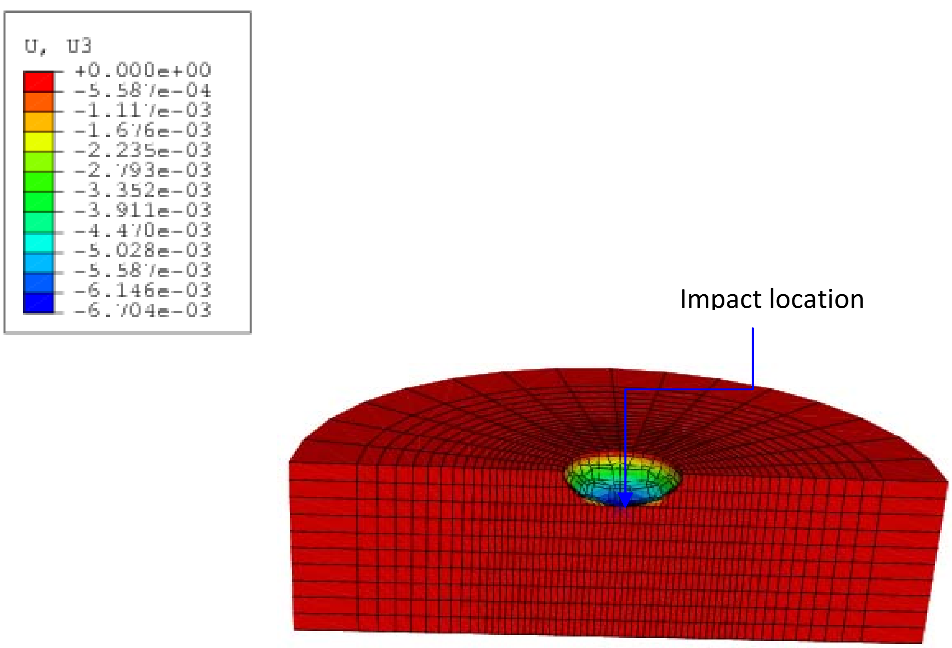

Figure 4.11 category 5 impact of debris on masonry

5. CONCLUSIONS

From this analysis it can be concluded that, the impact of compact windborne debris on cladding components is not negligible. Despite its less drag coefficient compared to other forms of debris, if the debris is a loose material such as stone or building material it starts moving when the wind loading exceeds its own weight. It can be well understood from parametric studies on some brittle materials like wood and masonry. Eventually this impact on cladding components may lead to serious external damage or even to breaching of the building envelope.

From parametric studies it was observed that for the impact of 2 inch diameter concrete roof tile:

- Roof tiles will become wind borne debris at category 1 hurricane and higher. It will damage windows if they are not protected by shutters.
- The maximum stress values for steel and aluminum at the location of impact were found to be in the elastic range due to this there was no permanent deformation observed; hence these materials are recommended for all category wind speeds for this size debris.
- 12 mm thick wood shutters are safe for categories 1 and 2 but needs to be replaced because there is noticeable penetration of debris, and for categories 3 and above this material is safe.
- Masonry has very small dents that can be repaired by patch work.

6. REFERENCES

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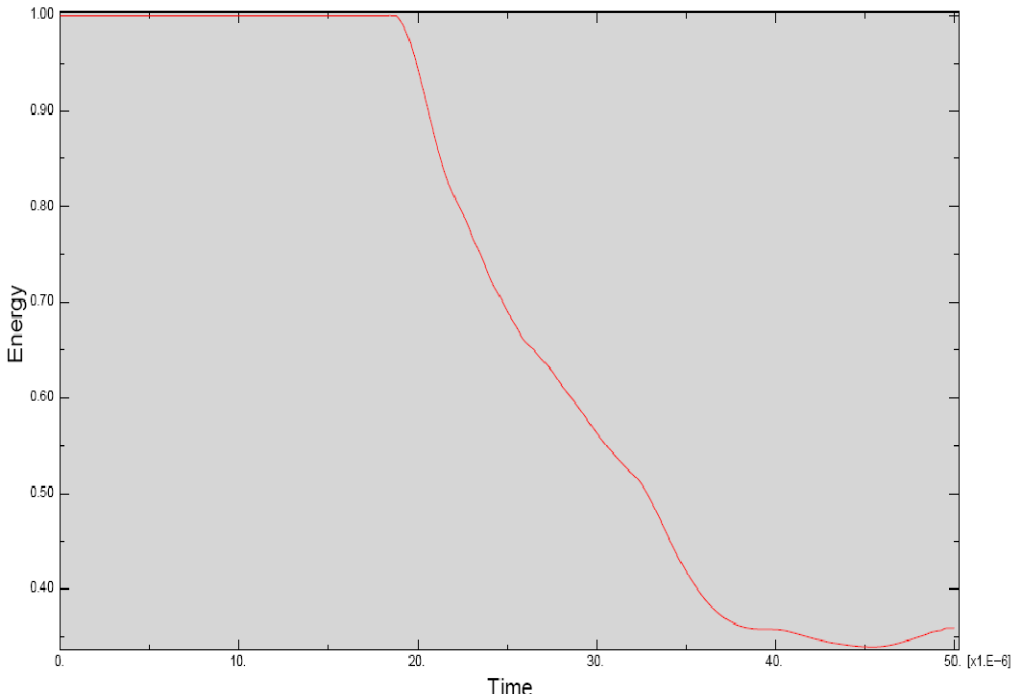
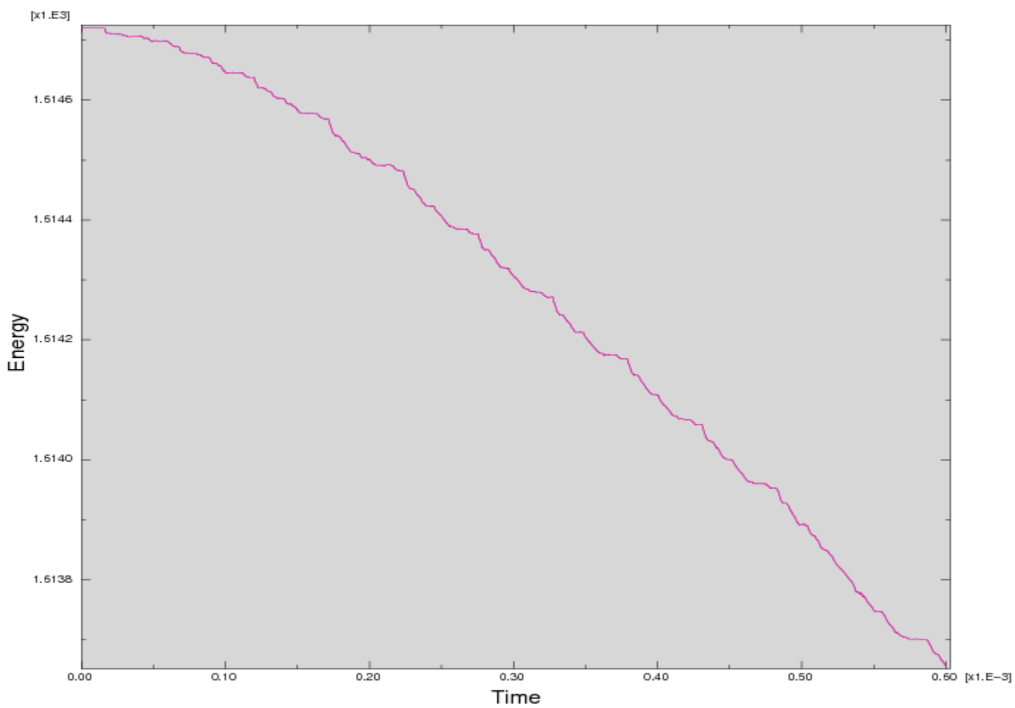
APPENDIX A Graphs for Kinetic Energy Obtained from Model Calibration

Glass:



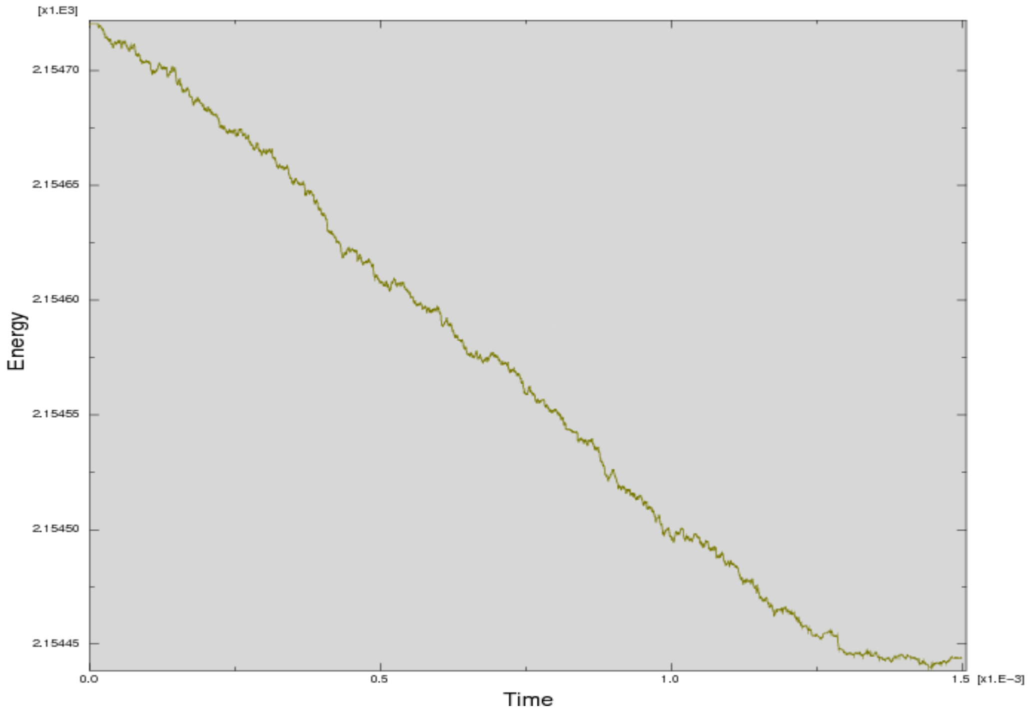
Kinetic energy for impact of 5gm steel ball on 0.006m thick tempered glass

Wood:



Kinetic energy for impact of concrete debris on 0.012m thick plywood

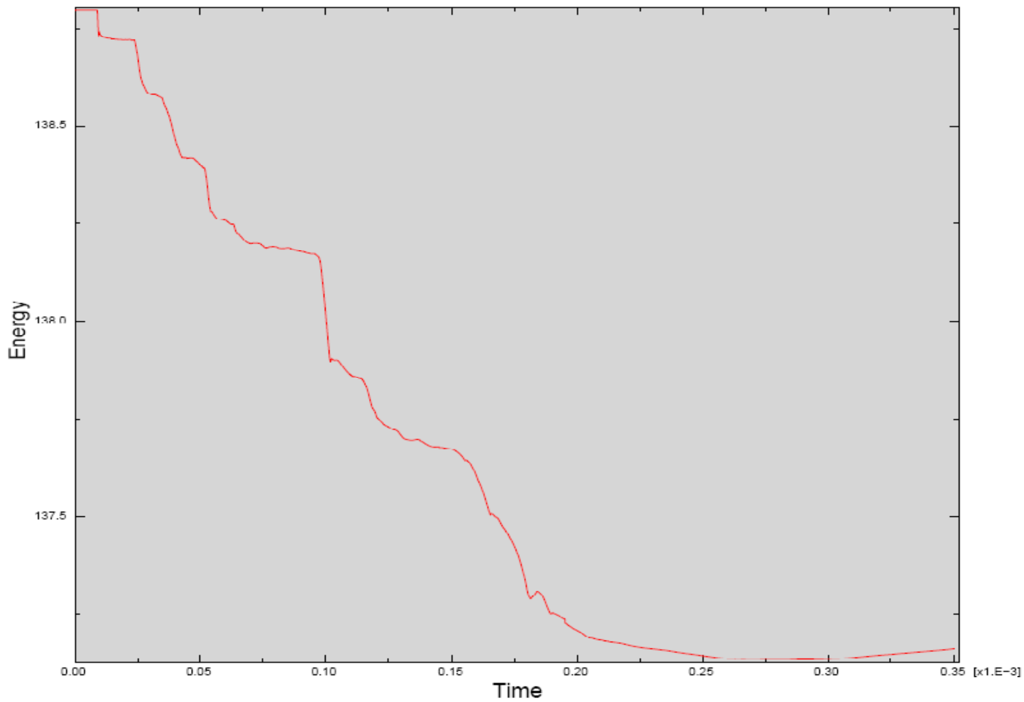
Masonry:



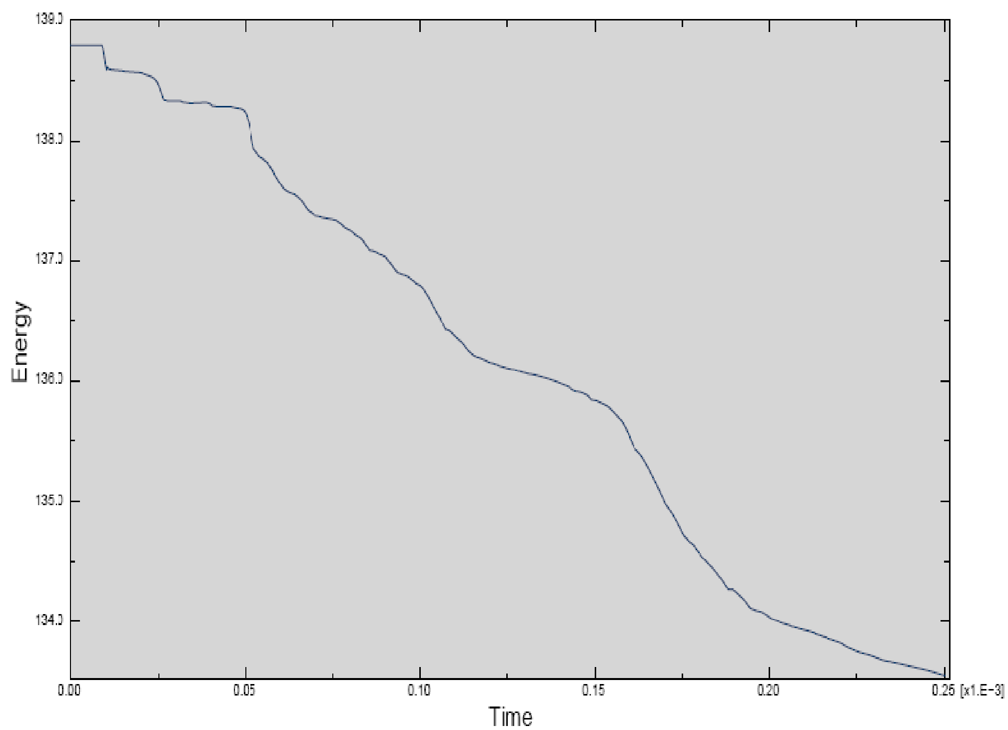
Kinetic energy for impact of concrete debris on 0.032 m thick masonry

APPENDIX B Graphs for Kinetic Energy Obtained from Parametric Studies

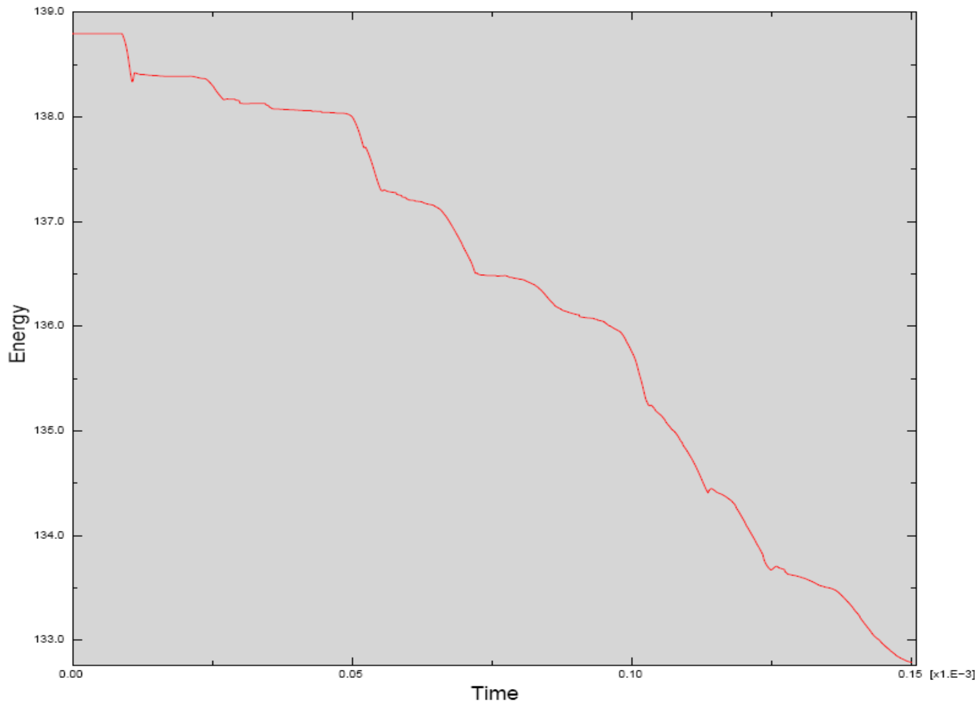
Glass:



Kinetic energy for category1 impact of debris on 0.002m thick glass

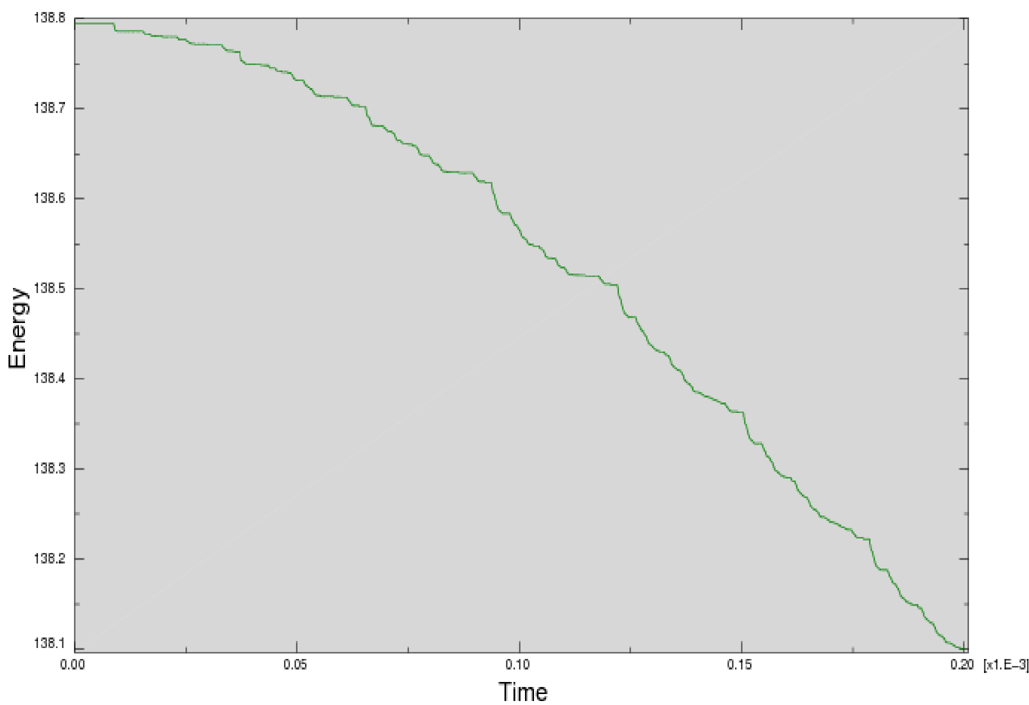


Kinetic energy for category1 impact of debris on 0.004m thick glass

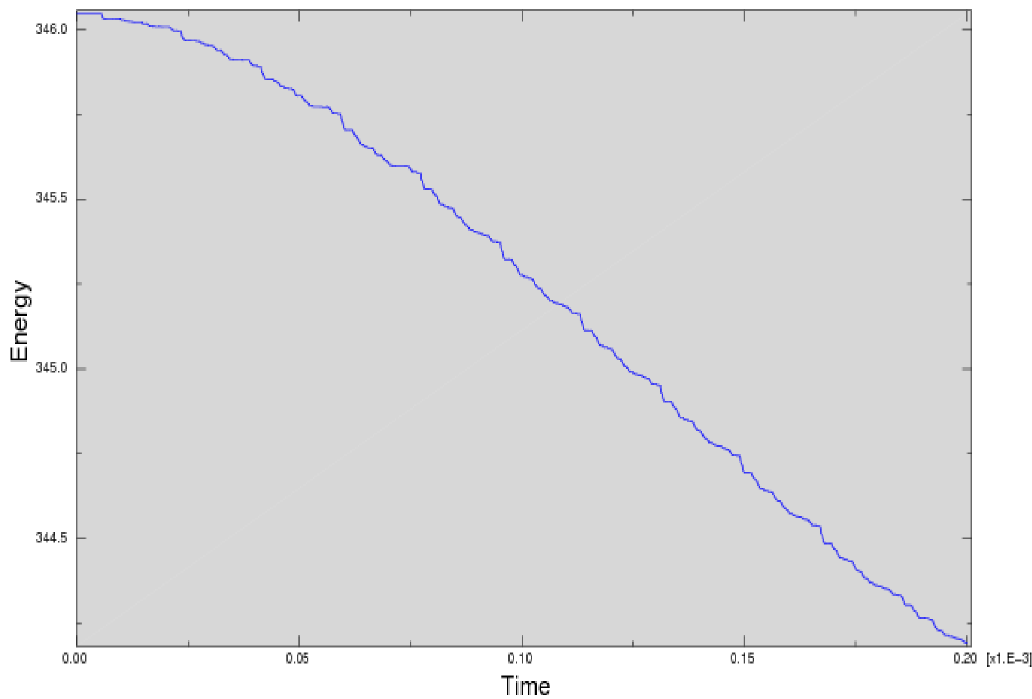


Kinetic energy for category1 impact of debris on 0.006m thick glass

Wood:

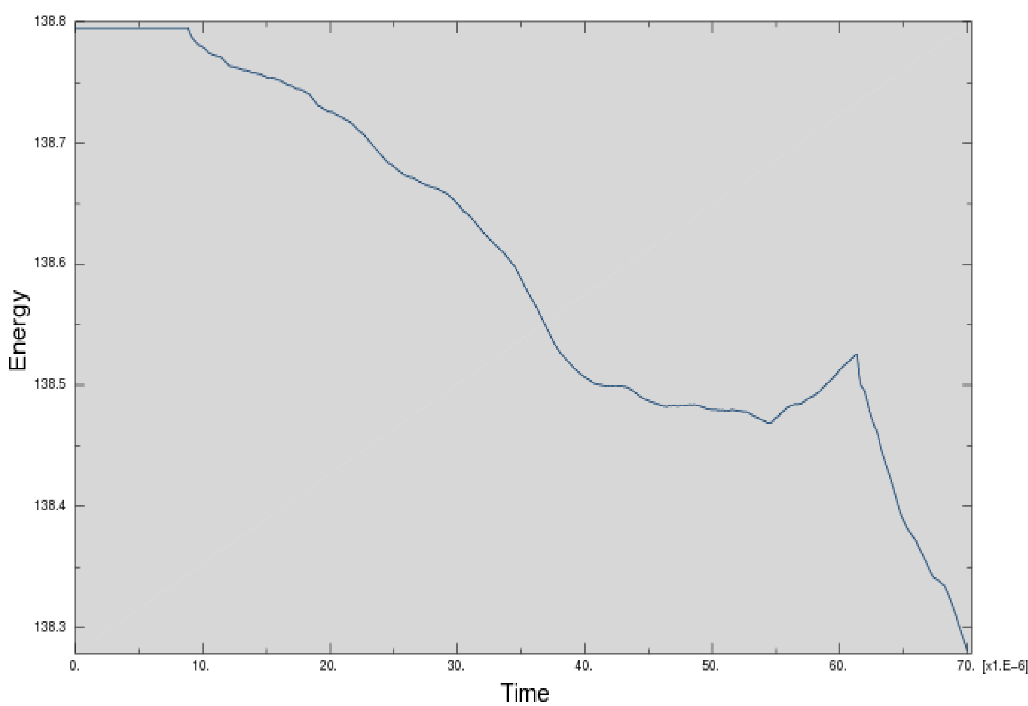


Kinetic energy for category 1 impact of debris on 0.012 m thick wood

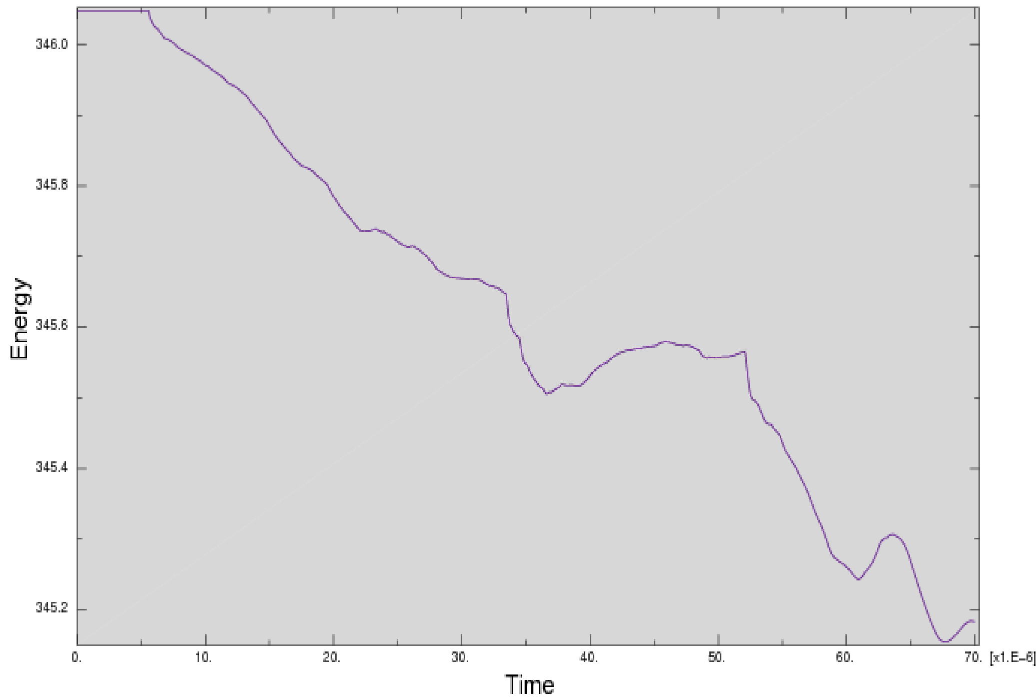


Kinetic energy for category 3 impact of debris on 0.012 m thick wood

Steel:

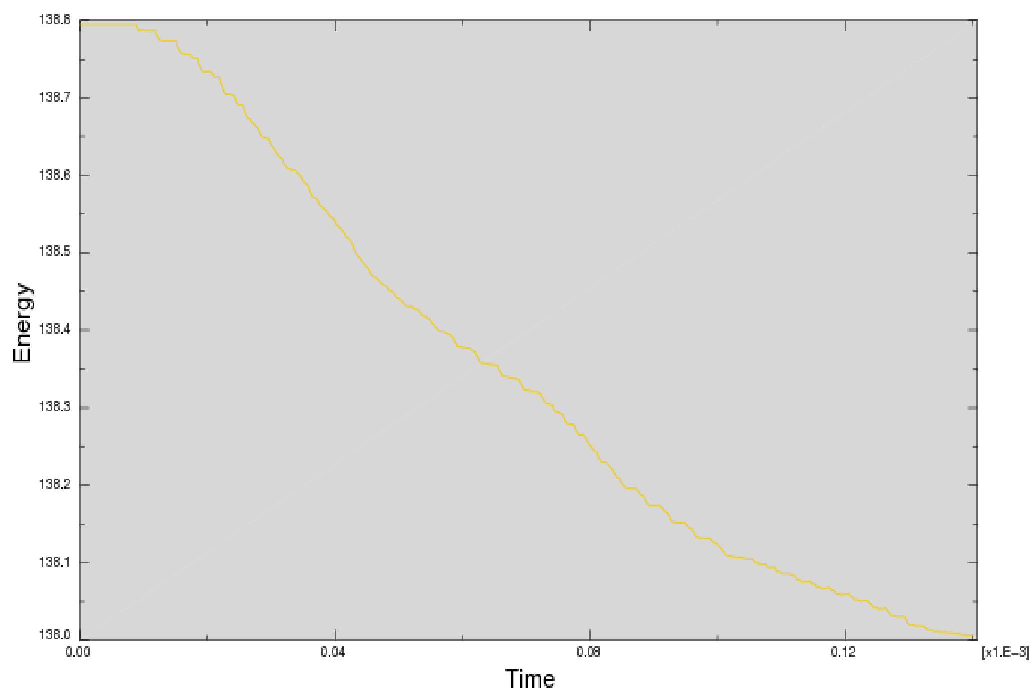


Kinetic energy for category 1 impact of debris on 0.0006 m thick steel

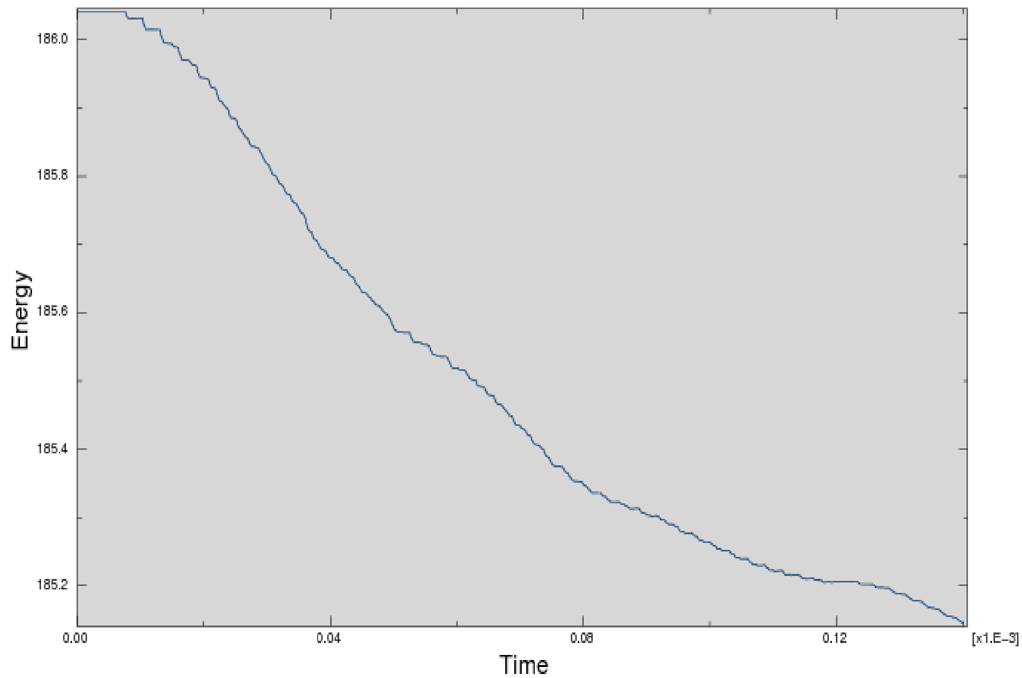


Kinetic energy for category 5 impact of debris on 0.0006 m thick steel

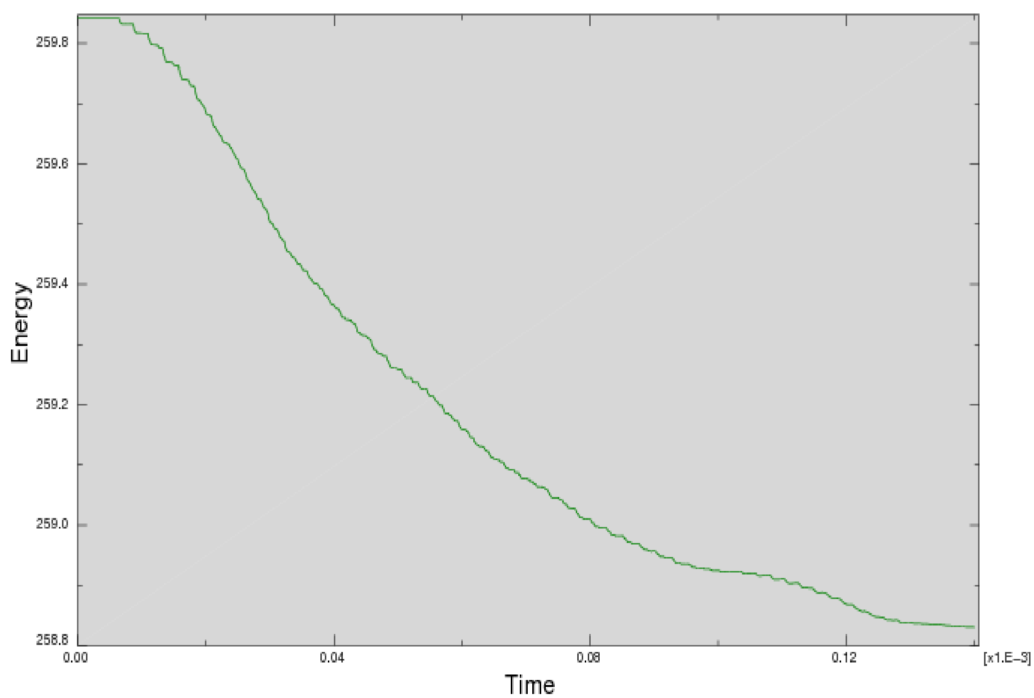
Aluminum:



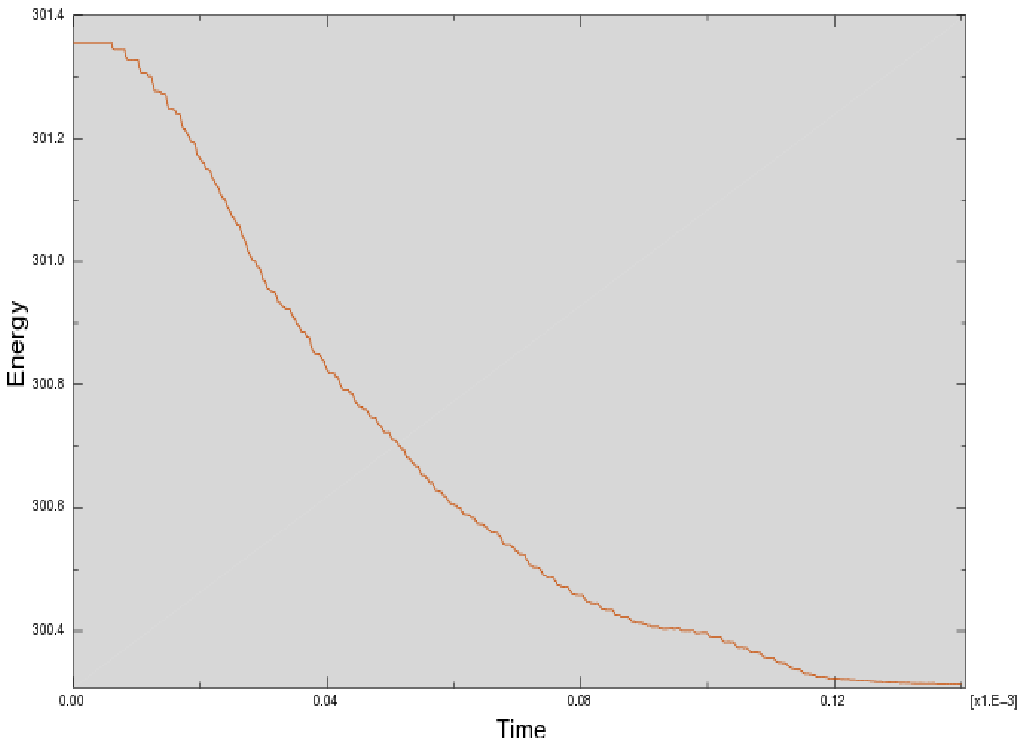
Kinetic energy for category1 impact of debris on 0.0013m thick Aluminum



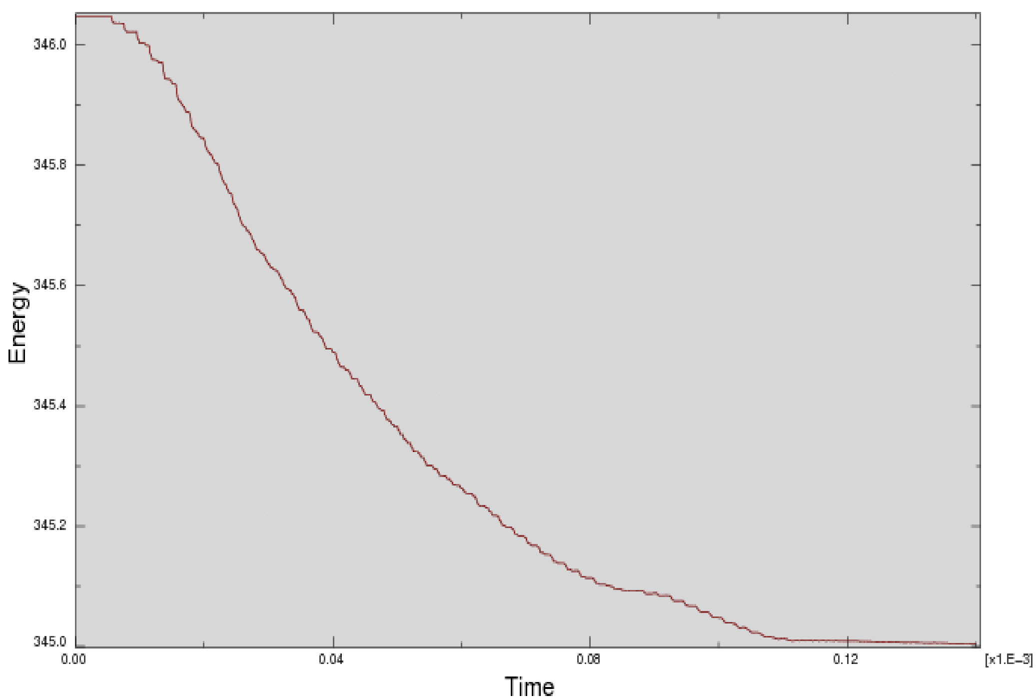
Kinetic energy for category 2 impact of debris on 0.0013m thick Aluminum



Kinetic energy for category3 impact of debris on 0.0013m thick Aluminum

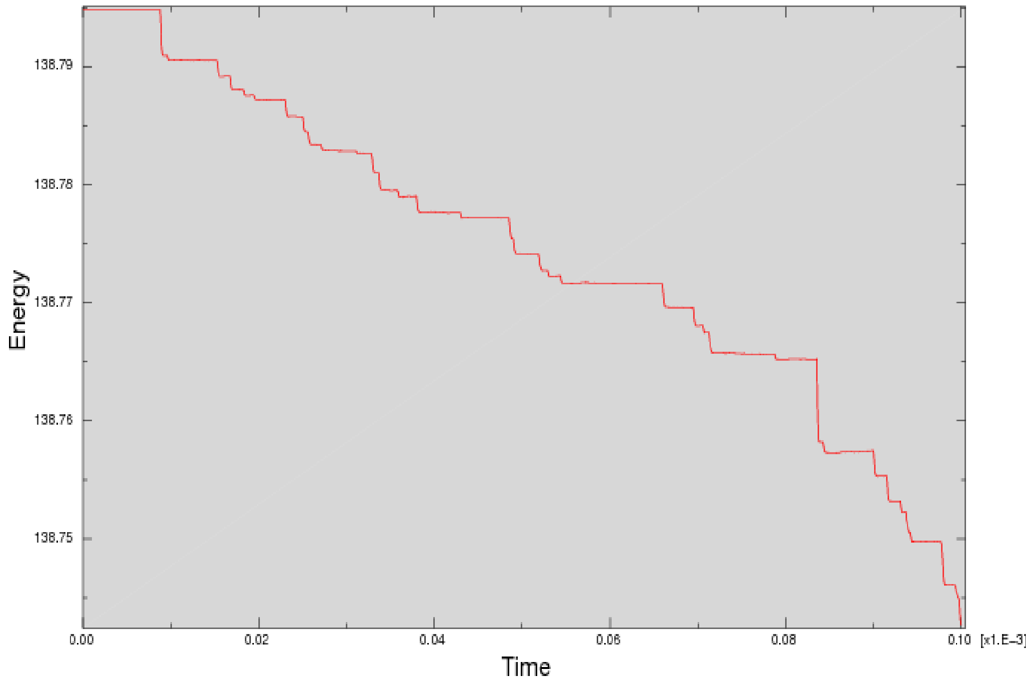


Kinetic energy for category 4 impact of debris on 0.0013m thick Aluminum

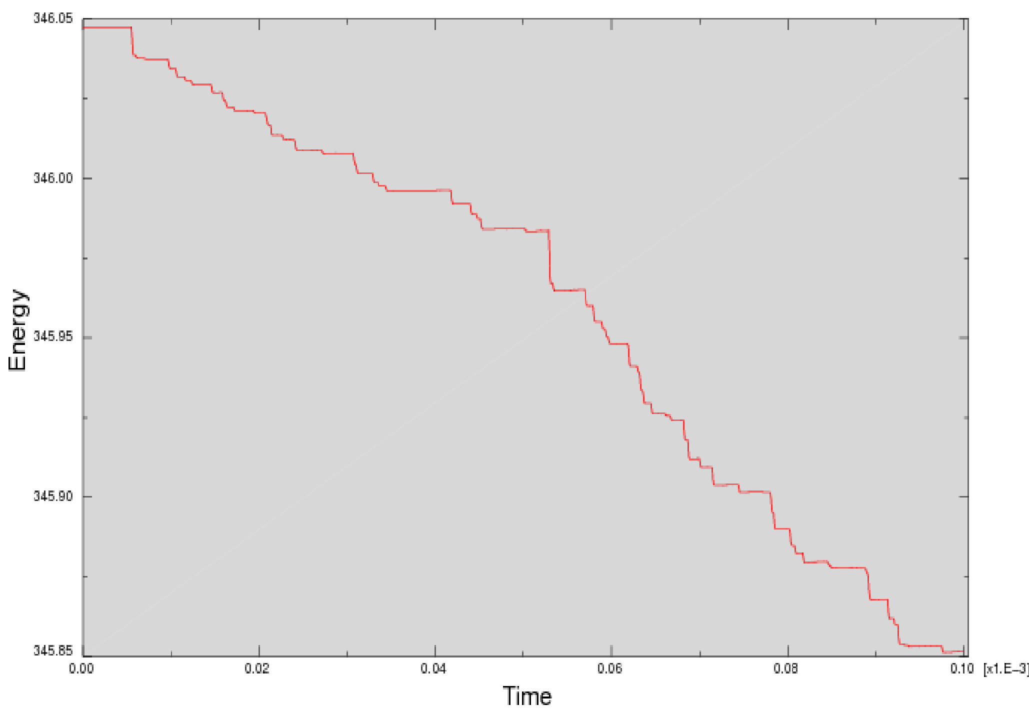


Kinetic energy for category 5 impact of debris on 0.0013m thick Aluminum

Masonry:



Kinetic energy for category1 impact of debris on 0.0317m thick masonry



Kinetic energy for category 5 impact of debris on 0.0317m thick masonry