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REPRESENTING A PRESSURE LOAD BOUNDARY CONDITION AS A RESULTANT ACCELERATION BOUNDARY CONDITION IN FINITE ELEMENT MODELING

Catherine S. Florio

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER

Munitions Engineering Technology Center

Picatinny Arsenal, New Jersey

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14. ABSTRACT

A comparative study was performed to understand how the representation of the driving load affects the predicted system response. Using a simple axisymmetric model of a canister partially filled with an epoxy subjected to a “drop” based impact event, the system behavior when subjected to a transient pressure-based load at the impacted surface was compared to the behavior when the entire outer surface of the canister was prescribed the bulk acceleration of the system calculated from the pressure used in the other model and the total system mass. The contact force and local accelerations within the canister as a result of the movement of the epoxy moved within the canister were compared between the two models. The maximum contact force and time of initial contact as the epoxy separated from the canister and moved toward an initially unloaded surface within the canister differed by approximately 15% between the models, within the variation that typically can be expected in experimental studies. However, the differing oscillatory responses after this initial impact indicate that the acceleration-based model may artificially stiffen the system when compared to the pressure-based model. Therefore, depending on the intent of the simulation, one representation of the environmental loads on the system may be preferable to the other. This study provides insight into the benefits and limitations of these two common methods of “driving” dynamic system behavior in a finite element model and can help aid in the selection of the means that may be suitable for a particular problem of interest.

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INTRODUCTION

Physical system can be studied through a combination of analytical, experimental, and computational models. Often, an experimental model is used to collect empirical data about the system properties or behavior, and this information is used in an analytical or computational model to gain further insight into the system behavior. Such insight can involve information about sensitivities to variations in other system parameters, the effects of design changes, or further understanding of behaviors or functions that are difficult to measure or control experimentally. The difficulty in gaining such information based on empirical data related to an external load is a result of the limitations in types and locations of physical measurements that can be made and the influence that the gages themselves may have on the system behavior that is being measured. Consequently, experimental measurements are sometimes made of responses to primary loads rather than measurements of the primary loads themselves. An example of this is experimentally measuring the displacement, velocity, or acceleration of a system with time rather than measuring the externally applied pressure or force that causes this displacement. Correlations between such a measurement and external load can be achieved through mathematical models based on laws and theories of science and engineering. Therefore, from an analytical viewpoint, these quantities can be interchangeable in terms of the bulk system behavior.

Such mathematical models, however, typically do not enforce the interchangeability of these measurements on the predicted system behavior when considering local responses, including the interactions of subcomponents within the systems. The numerical solution of these mathematical models involving finite element or finite difference methods further complicates the mere substitution of the experimental displacement measurement for the traction load. In such models, a set of equations is created for the local deformation at discrete points where forces are known and considered as boundary conditions. The equations at each of the discrete points where displacement (or velocity or acceleration) is known are excluded for the calculations, and the displacement at those points are directly applied to the equations for the unknown displacement at other points to which they are coupled through material property relationships. The approximation of the predicted behavior using such methods is compounded by the assumptions and simplifications that are made and the potential variability that may surround them, such as the laws that govern how components interact and the properties used in models that represent these interactions.

To bypass these potential sources of error and uncertainty, models can be created to represent the surrounding system from which the external loads are generated in addition to the system of interest. In this way, the external loads are calculated directly as part of the model. Examples of such surrounding systems can be experiment apparatus, neighboring and interfacing components, and environmental components, such as the ground or impact targets. However, these surrounding systems can often be complex, involving mechanisms to deliver a particular dynamic load that involve different physics states or energy states like fluids or combustion of explosives and propellants. They can also be large in size compared to the system of interest, such as when including the ground and impact targets. Further, many experimental tests have parameters and system components that are created and used simply to achieve a desired load condition or magnitude. Examples can be the use of bungee cords, impact pads, shims, spacers, impact shapers, explosives, or fluids not representative of the physical system being represented by the experiment. Modeling these components and the additional interactions can be quite computationally intensive and introduce more error, variability, and uncertainty than they were intended to resolve. Therefore, it often is not feasible to develop such extensive computational models, and decisions must be made on how best to represent the boundary and loading conditions with the given data collected from the experimental conditions.

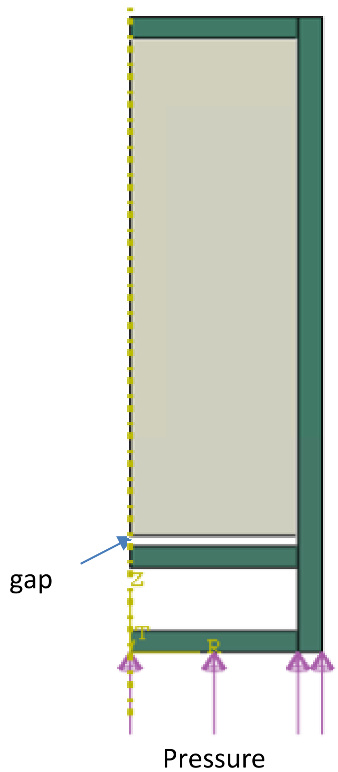
Anecdotally, "best practices" on measuring and representing external loads on different types of systems and under particular kinds of environmental conditions are often shared among those performing these kinds of analyses. For example, in the study of gun-launched projectiles, the question is typically whether to use an interior-ballistics model to estimate the base pressure on the projectile as the driving load of a computational model examining structural survivability of the projectile or whether to use data collected by an accelerometer that is mounted within the interior of the projectile. However, depending on the intent of the study and what is to be determined through the numerical simulation, the "preferred" method may change. Further, there are often no documented, quantitative studies that support the "best practices" stated, even for routine types of analyses. It is typical that for each new study encountered, a number of trials are performed to understand the sensitivity of the conclusions drawn from the study on, among other modeling assumptions, the way the loads and boundary conditions are applied to the system. The current study addresses some of these issues through the direct comparison of the predicted behavior of a simple system loaded either with a transient pressure load or through a corresponding acceleration load. The insight gained by the results of this work can be used to guide modeling decisions on the choice of boundary conditions and applied loads.

METHODS, ASSUMPTIONS, AND PROCEDURES

The work involved a representative system and a finite element model that were developed and used in a previous study (ref. 1). The system consisted of a metal cylindrical canister that was partially filled with an epoxy. The adhesive interface between the epoxy and the metal canister was modeled in such a way that the failure of the initially bonded interface was simulated. The system was subjected to an impact load, and the debonding and subsequent movement of the epoxy within the canister was modeled. In the current work, the impact load was represented in two ways: (1) through a transient pressure load on the base of the canister and (2) through an acceleration of magnitude corresponding to the pressure load and system mass that was applied to all exterior surfaces of the canister. Local accelerations and internal forces were tracked with time in order to compare the predicted response of the system under the two boundary conditions examined. Abaqus CAE 2019 was used in this work (ref. 2).

System Studied and Finite Element Model

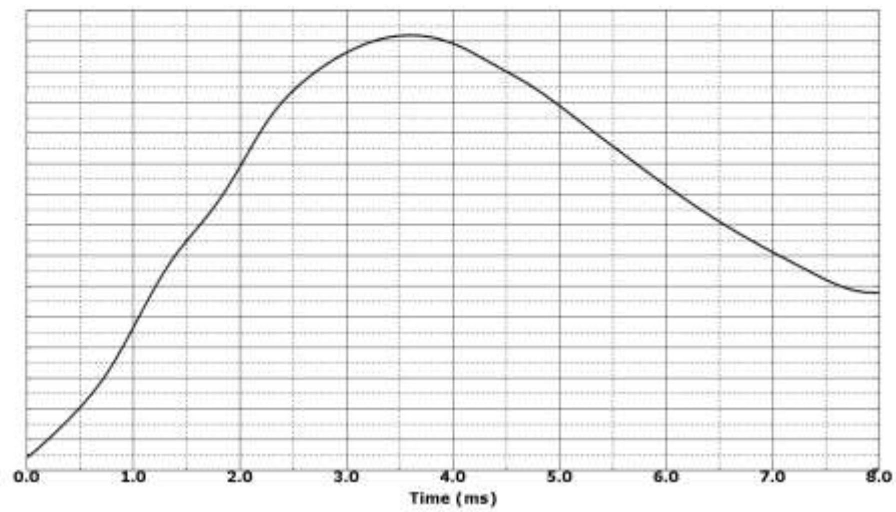
The system studied was a metal canister that was partially filled with an epoxy. The canister was 32 mm in diameter and 60 mm in height with a wall thickness of 2 mm. It consisted of two internal chambers: an upper chamber, which was 48 mm in length, and an inner chamber, which was 6 mm in length. The epoxy was located in the upper chamber filling all but the bottom 1 mm height of this chamber. It was initially adhered to the top and side surfaces of the interior surfaces of this upper chamber. The lower chamber was empty and used to separate the loading surface of the bottom of the canister from the surface used to measure the system response, the plate separating the two chambers. Two sets of boundary conditions were applied to represent the response of the system to being dropped against a compliant surface that was external to the canister system. The first load representation studied was through the application of a transient pressure applied to the base of the canister (fig. 1a). The maximum pressure was approximately 765 kPa, and the load was applied over 8 ms (fig. 1c). The second load representation studied was through the application of an acceleration to all outer surfaces of the canister (fig. 1b). The acceleration magnitude followed that of the pressure load (fig. 1c) and corresponded to that which would be achieved in the bulk motion of this system based on the pressure load and total system mass. The maximum acceleration was 8,400 m/s^2, or approximately 850 G.



(a)
System model with pressure load

(b)
System model with acceleration load

Figure 1
System studied



(c)
Dimensionless transient load curve

Figure 1
(continued)

The system was modeled using finite element methods with an axisymmetric approximation. The canister was represented with 500-μm elements, and the epoxy was represented with 40-μm elements. Linear quadrilateral axisymmetric elements with a reduced integration formulation and hourglass control were used for each system component. An explicit solver was used for this transient analysis. The timestep was approximately 4.5e-8s. The material and interface models will be discussed next.

Material and Interface Models

The system studied was comprised of two materials. The metal canister was aluminum, and the epoxy was Sylgard. This combination follows previously published studies (refs. 1 and 3). The material models and interface models are discussed in detail in reference 1 and will be briefly presented in this work. All material parameters used in this work are presented here and were selected based on the studies of reference 1, which examined the effect of these model parameters on the predicted separation of the epoxy from the canister wall.

Aluminum

The metal canister in this study was made of Aluminum 7075. A linearly elastic isotropic material model was used for this material, as failure/damage was assumed to be solely in the interface with the epoxy. The aluminum in this model had a density of 2,810 g/m^3, an elastic modulus of 71.7 GPa, and a Poisson’s ratio of 0.3.

Sylgard (Epoxy)

The epoxy studied in this work was Sylgard, represented as an isotropic, hyperelastic, nearly incompressible, rubber material. Following reference 3, the density of the Sylgard was 1,030 g/m^3, the initial shear modulus, μ_0, was 0.44 MPa, and the initial bulk modulus, k_0, was 1,214 MPa. The Poisson's ratio, ν, which represents the relative compressibility of this rubber, was found to be 0.4998 through the relation:

$$\nu = \frac{3\frac{k_0}{\mu_0}-2}{6\frac{k_0}{\mu_0}+2} \tag{1}$$

A built-in, neo-Hookean material model from the commercial finite element code Abaqus (ref. 2) was used to represent the epoxy material in this work.

Interface Model

A built-in, surface-based cohesive model of the commercial code Abaqus (ref. 2) was used to model the initial interaction of the Sylgard with the aluminum canister. Such a model can be used to represent an adhesive material that bonds two components without having to explicitly model the adhesive itself. This is of benefit in systems where a thin layer of adhesive is used, which would increase the computational requirements of the simulation were it to be modeled directly. While a large volume of epoxy exists in the system studied in this work, the use of the cohesive model is still valid and represents the region of the epoxy that contacts the interior wall of the canister.

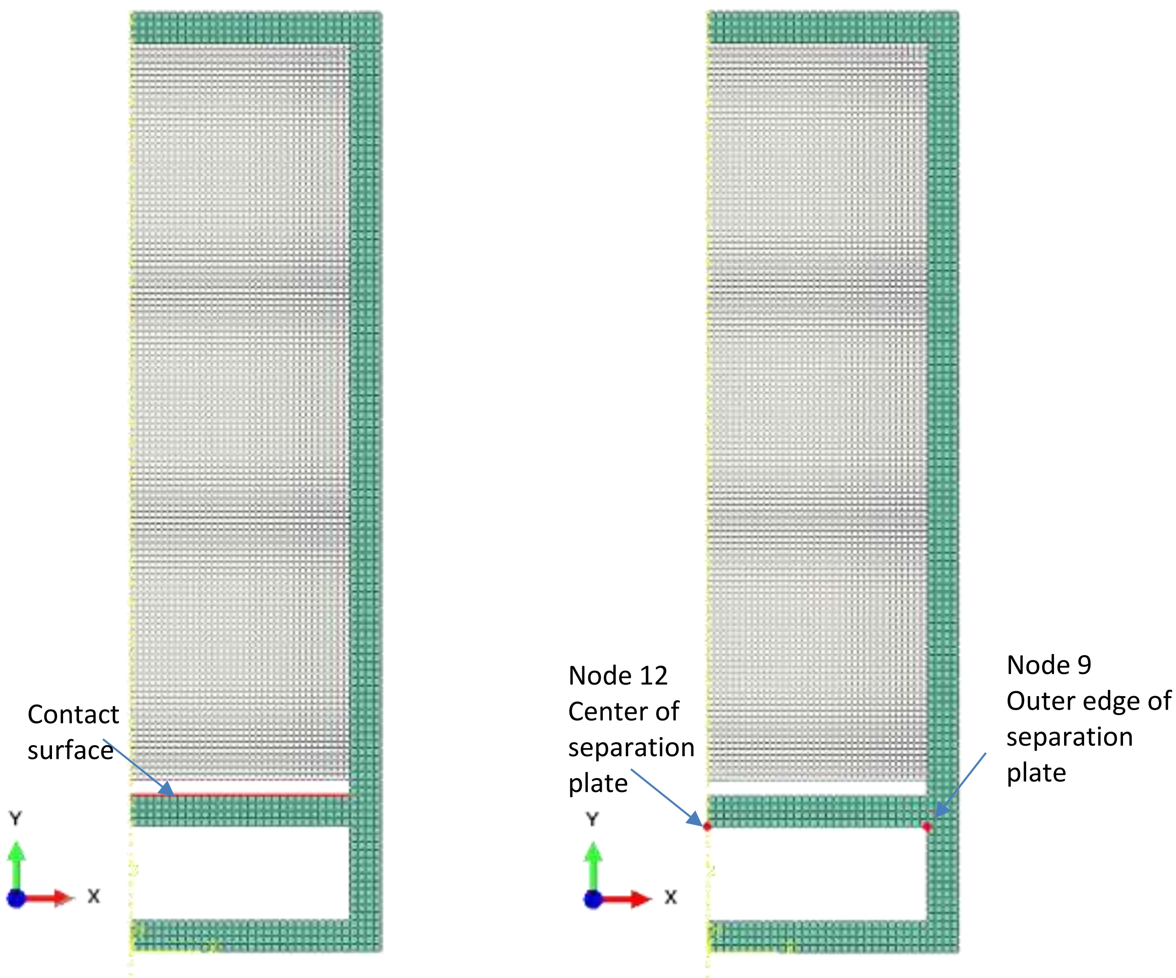
The built-in cohesive interface model in Abaqus controls the movement of slave nodes that are initially in contact for a predefined pair of initially adhered surfaces. A surface traction is calculated to simulate the forces generated between the bonded surfaces upon loading of one or both of the adhered components. This traction is proportional to the strain at these surface nodes due to compliance in the adhesive material being simulated by the cohesive interface model. The magnitude of this traction increases until a maximum threshold is achieved, and damage to the interface is then initiated. In this study, damage to the interface was initiated when this traction reached 10 kPa in tension. No compressive damage was assumed. Once initiated, the damage measure, *D*, evolved exponentially, based on the separation between the epoxy and the aluminum canister, δ_m^{max}, through the relation:

$$D = 1 - \frac{\delta_m^0}{\delta_m^{max}}\left(1 - \frac{1-exp\left(-\alpha\frac{\delta_m^{max}-\delta_m^0}{\delta_m^f-\delta_m^0}\right)}{1-exp(-\alpha)}\right) \tag{2}$$

In the model used, the exponent, α, was 9, and the maximum separation, δ_m^f, was 2.5 µm. The term δ_m^o in equation 2 is the amount of separation at the initiation of damage. Once the adhered interface failed, a penalty-based frictionless contact model was employed to simulate the post-adhesion interaction of the epoxy and the canister. For the materials and the loads applied in this work, this set of cohesive model parameters was previously found to induce full separation of the epoxy from the canister under the studied load and result in its subsequent contact with the separation plate (ref. 1).

Measures of Comparison

Four measures of the system behavior were used to compare the system behavior with the pressure-driven model and the system behavior with the acceleration-driven model. The contact force and the area of contact between the epoxy and the separation plate were tracked at each time step. Figure 2a indicates the surface from which the contact force and contact area was calculated. In addition to the contact behavior, the acceleration of two local points in the canister were tracked with time. One point was at the center of the bottom of the plate separating the upper and lower compartments of the canister. The other point was at the junction of this surface and the cylindrical wall of the canister. Figure 2b shows the nodes used in the acceleration comparisons. All of these measures were tracked at each timestep, and this data was then filtered with a second order Butterworth filter. Cutoff frequencies of 5, 10, and 25 kHz were all used. Upon comparison of the data filtered with these cutoff frequencies, only slight differences were noted in the magnitudes of the peaks and amplitudes of oscillations. The filtering had the greatest effect on the contact force, where only the highest cutoff frequency studied preserved the double peak in the initial impact induced in the acceleration-based model. Because this study was comparative, a low cutoff frequency was selected for most measures so that the “mean” curves could be better compared without the complication of varying oscillation amplitudes.



(a)
Surface for contact measures

(b)
Nodes for acceleration measures

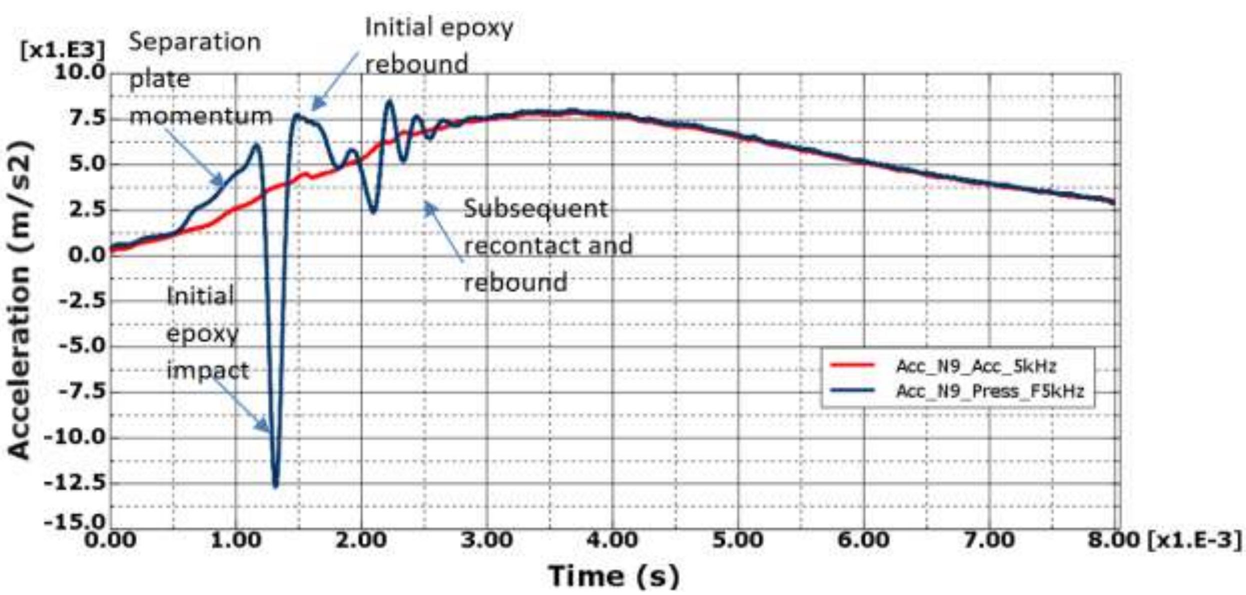
Figure 2
Locations of comparison measures

RESULTS AND DISCUSSION

In general, the acceleration-based model predicted that the system required more time for the epoxy to fully debond from the housing and impact the separation plate than did the pressure-based model. In addition, the acceleration-based model stiffened the system compared to the pressure-based model, resulting in more rigid contact/separation behavior of the epoxy as it impacted and rebounded off of the bottom separation plate after separating from the canister walls. Plots of the differences in each of the comparison measures and insight into the differences are presented in the following subsections.

Local Acceleration

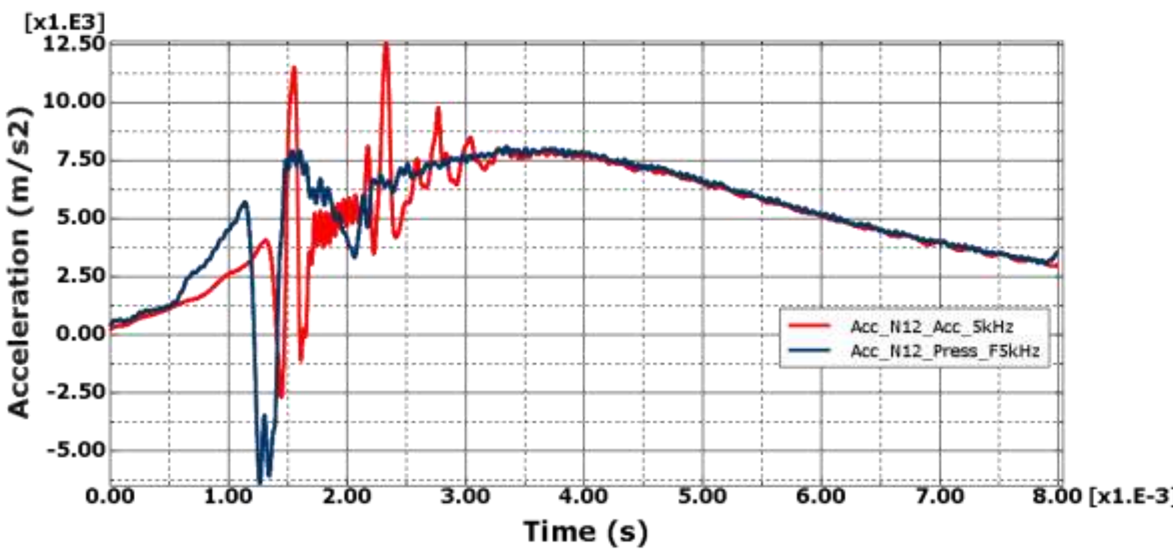
The local acceleration at a point on the separation plate at the juncture of this plate and the cylindrical wall of the canister predicted by the two models is compared in figure 3. In the model where a prescribed displacement (acceleration) is applied to all exterior surfaces, the local acceleration at this point, only 2 mm in distance from the applied boundary condition, followed the prescribed external acceleration (see the red curve in fig. 3). There was no deviation from the load curve in the acceleration at this point as a result of local interactions of the epoxy and the separation plate in the system. In contrast, in the model driven by a pressure load at the base, the effect of the impact of the epoxy on the separation plate was noticeable in the acceleration measurement at this point in the system (see the blue curve in fig. 3) The slight increase in acceleration as the mass of the plate responded to the movement induced by the pressure load is first seen, followed by the countering effects of the impact of the epoxy, its rebound, and subsequent oscillations (see the blue arrows in fig. 3). The behavior of the acceleration at this point at the bottom of the separation plate, despite being located at the juncture with the exterior wall of the canister, corresponded better to a physical explanation of the phenomena induced by the local response and interaction of the system components under an impact load. From the comparison of the acceleration at this point in the pressure-based and acceleration-based models, it is observed that the acceleration-based model locally stiffened the structure near the application of the prescribed displacement (acceleration).



Note: Blue curve is pressure-driven model; red curve is acceleration-driven model. Data is filtered at 5-kHz cutoff frequency.

Figure 3
Comparison of acceleration at node at edge of separation plate

The acceleration at the center of the separation plate is compared in figure 4. The acceleration-based model (red curve) resulted in a delay in the time of impact of the epoxy on the separation plate compared to the pressure-based model (blue curve). The acceleration-based model also resulted in a rebound acceleration that was greater in amplitude than the acceleration induced by the initial contact of the epoxy with the separation plate after the epoxy debonded and it was free to move within the canister. This disparity in rebound acceleration compared to the acceleration due to the impact with the separation plate was also seen in the subsequent oscillations. There is a period of time, from approximately 1.75 to 2.25 ms in the acceleration-based model where significant, high frequency, small amplitude acceleration oscillations result at this point. This behavior was not seen in the pressure-based model. The pressure-based model showed similar initial acceleration at the center point that was locally, relatively greater than the bulk system acceleration as was observed in the acceleration at the point in the plate near the wall (fig. 4). This occurred as the mass of the plate responded to the increased pressure load at the base of the canister. A large deceleration occurred next, corresponding to the movement of the mass of the epoxy against the separation plate in the direction opposite to that of the bulk of the canister. After this initial impact, a rebound acceleration occurred, though much smaller in amplitude than the rebound in the acceleration-based model. There was only one major subsequent re-impact of the epoxy in the pressure-based model. The oscillations due to the movement of the epoxy quickly “dampened” with time in this pressure-based model compared to the behavior of the acceleration-based model.

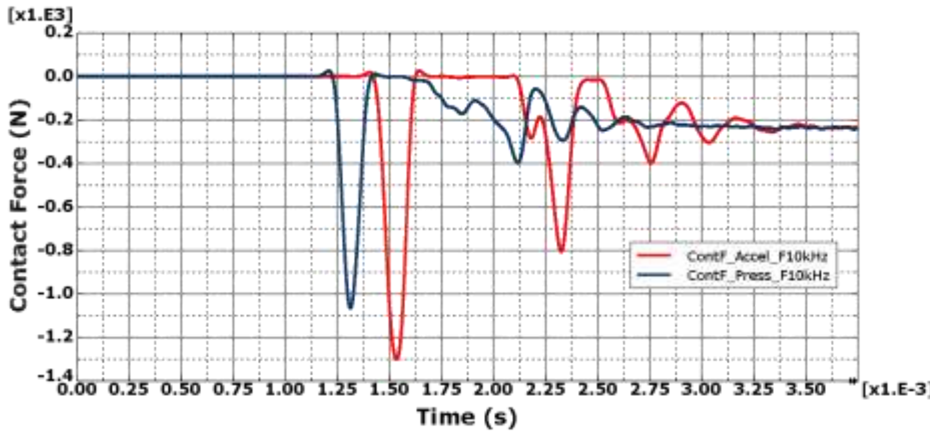


Note: Blue curve is pressure-driven model; red curve is acceleration-driven model. Data is filtered at 5-kHz cutoff frequency.

Figure 4
Comparison of acceleration at node at center of separation plate

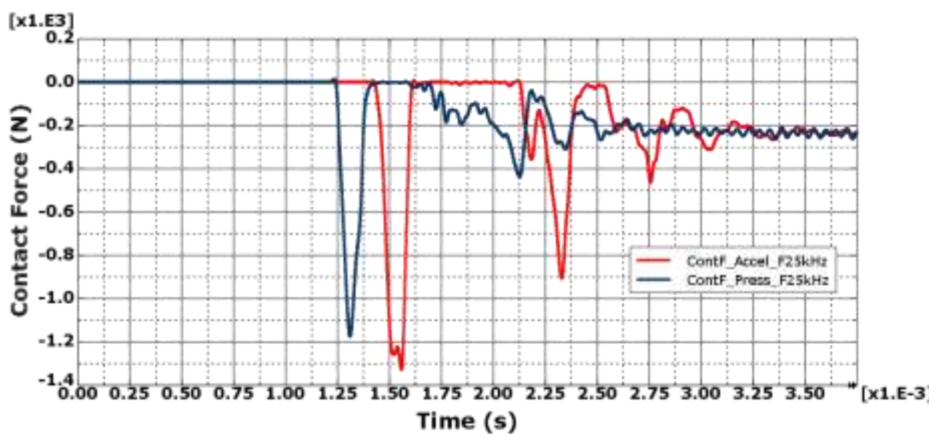
Contact

When comparing the contact force variations with time (fig. 5), two important trends are noted. First, the acceleration-based load resulted in approximately a 15% increase in the time to initial contact between the epoxy and the separation plate and approximately a 15% increase in the magnitude of the initial contact force compared to the pressure-based load. Second, the acceleration-based load had an extended period of separation from the plate, from approximately 1.75 to 2.25 ms, and a second substantial contact force that occurred when the epoxy again contacted the separation plate. This second contact force was about 60% of the magnitude of the initial contact force. This was then followed by a shorter period of separation and then small oscillations where the two components remained in contact but the magnitude of the contact force increased and decreased before settling in a constant force that corresponded to the weight of the epoxy. In contrast, the pressure-based load had a very short period of separation after the initial contact between the epoxy and the separation plate, followed by a gradual increase in contact force and smaller oscillations in contact force before gradually damping to the same constant contact force as seen in the acceleration-based model. Therefore, while the difference in the maximum contact force predicted by each model was relatively small and both models settled into the same "steady state" contact force, the pressure-based model predicted a somewhat more gentle interaction between the epoxy and the separation plate than did the acceleration-based model.



Note: Blue curve is pressure-driven model; red curve is acceleration-driven model.

(a)
Data filtered at 10-kHz cutoff frequency



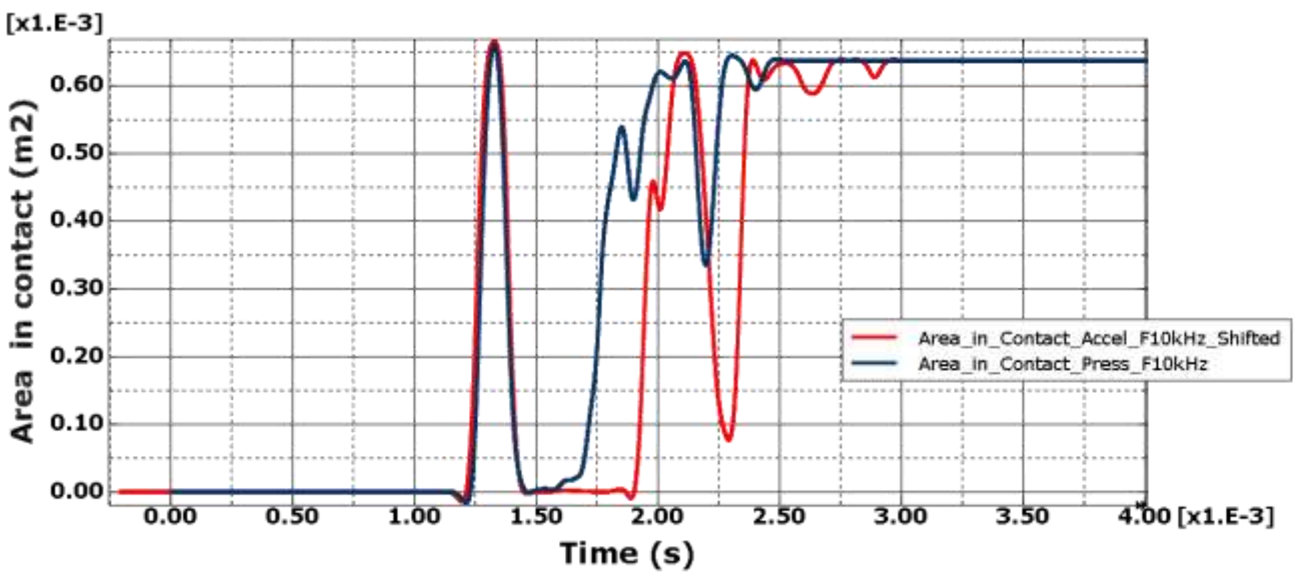
Note: Blue curve is pressure driven model; red curve is acceleration driven model.

(b)
Data filtered at 25-kHz cutoff frequency

Figure 5
Comparison of contact force on separation plate

Comparing figures 5a with 5b, the double peak at the initial contact of the acceleration-based model was seen with the higher cutoff frequency of filtering, though it was missing when the lower cutoff frequency filtering was used. In addition, the filtering with the lower cutoff frequency smoothed many of the abrupt transitions in contact force magnitude for both models. While the difference did not significantly affect the intent of this comparative study, caution should be used in the selection of the cutoff frequency when concern is with the accuracy of the model prediction.

In figure 6, the area of the separation plate that is in contact with the epoxy at any given time in the study is compared for the two different models. For ease of comparison, the curves were shifted so that the initial contact peaks are overlaid. Examining the curves in this manner can provide insight into the differences in the behavior predicted by each model that were noted through the comparisons of the contact force and local accelerations. Overall, the shapes of the curves are comparable. After the initial brief time of full area connect, there was a short time of complete separation followed by oscillating extent of contact before full contact is finally sustained. The basic trend of the oscillatory levels of contact is also consistent between the models. After the initial separation, there was a short period of partial contact, slightly less extent of contact (or a trend toward separation), followed by nearly full contact and then a more significant decrease in contact area as a trend toward separations again occurred. This was then followed by full contact again and small oscillations, indicating slight separation before sustained, full contact.



Note: Blue curve is pressure-driven model; red curve is acceleration-driven model. Data filtered at 10-kHz cutoff frequency.

Figure 6
Comparison of contact area on separation plate with time shifted to match first peak

Differences between the models are related to the differences in the duration and magnitude of the contact area during each of these noted phenomenon. The time of initial full contact was the same for both loading type models. However, the time of full separation was much longer, approximately 0.5 ms, for the acceleration-based model compared to the pressure-based model, where separation lasted for less than 0.1 ms. The gradual increase in contact area of the pressure-based model resulted in a smaller amplitude and duration of trend in decreased contact area toward separation and smaller amounts of oscillations before a stable configuration was reached. The more abrupt changes in the contact area of the acceleration-based model resulted in nearly four times the reduction in contact area upon this second major “rebound,” greater subsequent oscillations, and a

40% longer overall time to reach a stable configuration after the initial impact event than occurred in the pressure-based model.

General Observations

Through the comparisons of local acceleration, contact force, and area of contact, some insight can be gained regarding the differences between using a pressure load or an equivalent bulk acceleration to “drive” the transient behavior of a structural system. Using an acceleration applied to the outer surface of a structure tends to stiffen the overall system. This is because the degree of freedom of these surface nodes in the direction of the load is removed when it is prescribed with a given acceleration. Those surface nodes are, therefore, removed from the calculations of deformation in this direction in the finite element solution. Thus, rather than calculating the displacement behavior based on the propagation of the stress waves that result from the impact load, the displacement of these surface nodes in the direction of the main motion nodes is pre-defined in order to create the bulk behavior of the system. Therefore, the stress wave propagation, reflection, and interaction through the system components, which are part of the physical response of the system to the highly transient load, are not directly predicted by an acceleration-based finite element model. This is a limitation of using a locally measured acceleration as a representation of the bulk system behavior.

In the canister example studied, the separation plate can be considered as a “trampoline” upon which the rubber-like epoxy impacts. The greater the “tension” in this plate (the stiffer it is), the greater the rebound behavior and post-impact separation. The looser the tension (the more compliant the trampoline is), the more gentle rebound behavior, although it results in more complex interactions through deformation in each component and load sharing. The more rigid contact-separation behavior observed in this study for the model driven by an acceleration load is an indication of a “stiffer” separation plate compared to that of the model which was “driven” by a pressure load applied to the exterior base of the canister, a location far from the separation plate. The duration of the time of the zero magnitude contact force between the epoxy and the separation plate in the acceleration-based model corresponded to the duration of time where high frequency small amplitude acceleration oscillations developed at the center of the plate. This phenomenon was not seen in the pressure-based model. It is likely an artificial response to the stiffening of the system that resulted from the displacement-based load used. Therefore, further calculations using data from such a model, such as to identify local vibrational characteristics, will carry this artificial effect of the imposed boundary condition.

CONCLUSIONS AND RECOMMENDATIONS

This study compared the predicted behavior of a system subjected to an impact load through a model that is driven by a pressure load at the impact surface with a model that is driven by an acceleration boundary condition applied to all exterior surfaces of the system. The pressure-based model may be more representative of the physical conditions because it represents the primary loading measure. However, the pressure magnitude and variation with time may be difficult to measure experimentally. The acceleration-based model drives the system with a secondary measure that is a result of the physical conditions rather than the cause of the physical conditions. However, experimentally, a transient local acceleration is relatively easy to measure, providing a specific record of the local system behavior in “real life” conditions. In the simple system studied in this work, the influence of the applied load/boundary conditions on the interactions of the two system components were compared through measures of local acceleration and contact force on an interior plate as an epoxy component moves against it, within the canister in which it is housed.

The study found that the response to the initial impact event, the first peak of the contact force between the components, varied only 15% between models. This is well within acceptable experimental variation. However, the subsequent interaction behavior, the response to this first interaction, varied more significantly between the two models. The acceleration-based model was found to artificially stiffen the system. This resulted in a significant period of separation of the epoxy from the contact plate after their initial impact. As a result, a notable “ringing” of the plate occurred, followed by a more severe re-impact of the epoxy on the plate and greater amplitude and time of oscillation until the two system components again began to move as a unit. The pressure-based model well represented the local deflection of the separation plate prior to the impact with the debonded epoxy that results from the plate’s mass inertia and the stress wave propagation from the impact of the base of the canister system with its environment. The interaction between the rubber epoxy and aluminum plate was more “gentle” as the plate was more compliant in the pressure-based load model, allowing it to move more directly with the influence of the epoxy. While this resulted in more complex interactions between the epoxy and the separation plate of the canister, it allowed for greater damping of the oscillations induced by the impact between the two system components and a quicker return to their unified motion.

Depending on the intent of the study, some recommendations can be made to guide the decision between modeling a pressure-based or an acceleration-based load for this kind of impact event:

- If only the initial peak behavior is of interest, either model is likely sufficient to estimate the general response to the external load. This is especially true when comparing to experimental results, as the difference in the maximum contact force and time to contact varied less than 15% between the two models, well within expected experimental variation.
- If the interaction behavior is of interest, a pressure-based model will better predict the physical phenomena without artificial phenomena introduced due to the numerical solution.
- If the study interest is related to predicting likelihood of structural failure due to the interaction of internal components, an acceleration-based load may produce more severe conditions, adding a factor of safety to the survivability prediction.
- If the accurate prediction of the interaction behavior is of interest, and subsequent calculations will be made based on model data, such as vibrational analyses, a pressure-based model is recommended.
- If the physical pressure load cannot be readily measured, or can only be estimated when an analysis calls for understanding the behavior of a specific system condition, an experimentally-measured acceleration-based load can be used as long as the limitations discussed in this work are well understood.

In addition to the insight gained, the presented work provides a framework through which a simple comparative study can be performed for a particular system of interest in order to understand the sensitivity of the behavior to the representation of the external loads for a model that is being developed to address a particular question.

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