

Stable and Accurate LS-DYNA Simulations with Foam Material Models: Optimization of Finite Element Model Parameters

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ABSTRACT

Cellular foams have found a predominant application in automotive industry for efficient energy absorption so as to meet stringent and continuously improving vehicle crashworthiness and occupant protection criteria. The recent inclusion of pedestrian protection regulations mandate the use of foams of different densities for impact energy absorption at identified impact locations; this has paved the way for significant advancements in foam molding techniques such as dual density and tri-density molding. With increased emphasis on light-weighting, solutions involving the use of polymeric or metallic foams as fillers in hollow structures - foam encapsulated metal structures - are being explored. Another major automotive application of foams is in the seat comfort area, which again involves foams of intricate shapes and sizes. In addition, a few recently developed foams are anisotropic, adding on to the existing complexities. Complexities associated with controlled/uncontrolled spatial variation in density and the geometry of molded parts and use of foams in sandwich composites offer several challenges for the CAE community in modeling the foam components.

As a first step to capture these complexities, optimal settings of available LS-DYNA modeling features have to be determined to enable effective Finite Element Analysis (FEA) of foam components. This paper aims to investigate the various underlying parameters such as element formulations and size, contact stiffness and hourglass control, governing stability and accuracy of foam material models and to identify the optimal settings of these parameters. The optimal settings for the identified parameters are elucidated in the context of the rate dependent foam model in LS-DYNA (Fu-Chang Foam).

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INTRODUCTION

Stringent and continuously improving vehicle crashworthiness and occupant protection regulations, from various regulatory bodies around the world, have led to considerable efforts in experimental and analytical investigations to improve the crashworthiness of vehicle structures so as to protect the occupant. Cellular foams are known for efficient Energy Absorption (EA) [1, 2, 3, 4, 5] and hence have found predominant application in vehicle structure. These EA foams are used in laminated parts for interior energy management, front and rear bumpers, side-impact bolsters and also as counter measures in head impact protection applications. The foam structures in automotive application are often forced to take complex shapes due to various packaging constraints such as space, shape, styling etc. The energy absorption capability of foam changes with density, hence

medium to high density foams find their suitable applications for EA applications. Expanded Polypropylene (EPP) foams of 60-120 kg/m³ are widely employed for automotive EA applications for crash scenarios [6, 7]. The recent inclusion of pedestrian protection regulations mandates the use of foams of lower density for EA at identified impact locations. EPP foams of densities typically in the range 20-45 kg/m³ and rigid polyurethane (PUR) foams with densities 50-70 kg/m³ are generally employed to meet pedestrian-protection requirements [6, 7]. Meeting these varied load-case requirements within the same subsystem has been enabled by significant advancements in the processing techniques resulting in dual density molded or tri-density molded foam parts [7, 8, 9, 10]. With demands for light-weighting as a potential solution to meet regulatory demands on fuel efficiency, there are many studies with

polymeric or metallic foams used as fillers in hollow structures and foam encapsulated metal structures, improving the structural strength and energy absorption capabilities [11, 12, 13, 14, 15]. Another major automotive application of foams is in the seat comfort area which also involves intricate shapes and sizes. A few recently developed foams are anisotropic, adding on to the existing complexities.

Complexities associated with controlled/ uncontrolled spatial variation in density and the geometry of molded parts and use of foams in sandwich composites offer several challenges for the CAE community to model the foam parts. As a first step to capture these complexities and enable effective design of foam components, optimal settings of available CAE material models for modeling foams have to be determined.

This paper investigates various underlying parameters governing stability and accuracy of foam material models with the aim of identifying their optimal settings to accurately represent the rate-dependent characteristics of a commercially available polyurethane (PU) foam. The parameters and their optimal settings are elucidated in the context of LS-DYNA rate dependent Fu-Chang Foam model. Subsequently, the same optimal parameter settings are used to compare simulation and test results at sub-system level with pedestrian protection (ped-pro) loadcases. Results from tetrahedral and hexahedral meshing are compared for ped-pro and exterior load cases.

LS-DYNA FOAM MATERIAL MODELS

LS-DYNA library of material models contains several dedicated models for highly compressible solids such as cellular foams. The choice of a material model to simulate foams is not straightforward because of the wide range of options available on the basis of the type of behavior that needs to be simulated. Predominant use of foams in automotive industry is for EA at low, medium and high speed impacts; this warrants the use of material models that can account for rate dependent compression behavior of foams. Further, at high or medium speed impacts, the foam parts are subjected to complex stress states causing fracture; such fractures are often due to localized tension or shear and bending. Hence, it would be relevant to additionally account for the rate dependent tensile behaviors in the material model. Low Density Foam model (MAT_57) is a widely used 'curve-fit' based foam material model due to the simplicity it offers in defining basic foam characteristics but it is limited in its use since it can take only rate independent information. Hence, it may not be suitable for modeling foam parts subjected to a varying strain rate. Another material model option is a Crushable Foam model (MAT_63/163) which can utilize strain rate dependent compression information but does not account for the tension behavior or the actual recovery characteristics. Fu-Chang Foam model (MAT_83) is comparatively a more comprehensive material model that can account for rate dependent compression and tension. More details for each of the models can be found in [16, 17].

Additional layers of complexity such as time-dependent behavior (viscoelasticity, as described using a multi-mode Maxwell model), can be implemented using a Viscous Low Density Foam model (MAT_73). Hill Foam model (MAT_177) describes a highly compressible foam based on Hill's strain energy function, and Viscous Hill Foam model (MAT_178) includes large strain viscoelasticity. Deshpande-Fleck Foam model (MAT_154) is generally recommended to model aluminum honeycombs and foams used as filler material in aluminum extrusions to enhance energy absorption capability. Models implementing a detailed recovery and viscoelastic behavior may be of great relevance to comfort and / or vibration transmissibility studies. Since the EA performance of polymeric foams is of primary interest in this study, Fu-Chang Foam model is considered to model a commercially available EPP foam.

Figure 1 schematically represents the parameters that may affect the stability and accuracy of estimates from Fu-Chang Foam model. Geometrical aspects (related to mesh and element formulation), numerical parameters, as well as parameters specific to the Fu-Chang Foam model are considered.

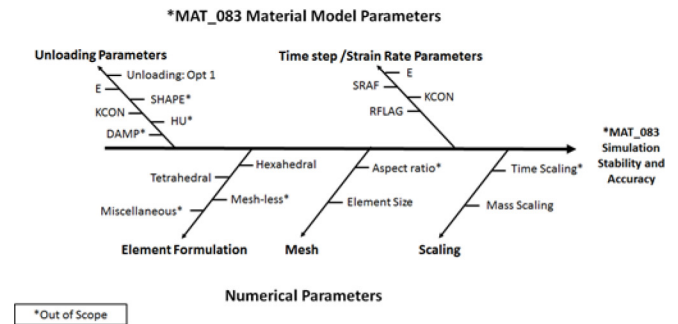


Figure 1. "Fishbone" diagram showing the factors impacting stability and accuracy of compression simulations employing Fu-Chang Foam material model.

ELEMENT FORMULATION

This section assesses the applicability of various solid element formulations (Figure 2) to represent the polymeric foam components. Solid elements can be classified into first or second order - hexahedral and tetrahedral elements. Generally, second order elements are computationally expensive and unstable for complex contact problems. Therefore, these elements are not used in full vehicle level simulations. Different first order hexahedral element formulations are, constant stress solids (ELFORM 1), fully integrated selectively reduced solids (ELFORM 2) and fully integrated 8-noded solids with rotational degrees of freedom (ELFORM 3). Different first order tetrahedral element formulations are, constant stress solids (ELFORM 10), constant stress solids with nodal pressure averaging (ELFORM 13), and fully integrated 4-noded solids with rotational degrees of freedom (ELFORM 4).

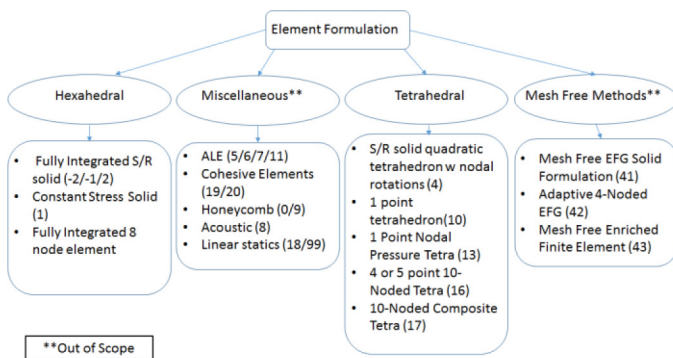


Figure 2. Element formulations evaluated for simulation of compression with the Fu-Chang Foam model.

ELFORM 1 is an underintegrated element suitable for severe deformations. Hence, it is prone to hourglass modes and requires hourglass stabilization. The choice of hourglass stabilization is complex. This study employs viscous (IHQ=3) and stiffness (IHQ=5) based hourglass controls with the hourglass coefficient, QH set to the recommended default values. ELFORM 2 is a selectively reduced integrated element with volumetric locking alleviated. This formulation is prone to shear locking while representing elements with poor aspect ratios. Enhanced strain formulations using a modified Jacobian matrix resolve the shear locking while representing elements with a poor aspect ratio. These modifications are implemented as ELFORM -1 - an efficient formulation, and ELFORM -2 - an accurate formulation [18]. ELFORM -1 and -2 are respectively, 1.2 and 4 times computationally more expensive than ELFORM 2. It should also be noted that ELFORM -1 may hourglass. ELFORM 10 is a 1-point constant stress element prone to volumetric locking, hence it is recommended for foams with zero Poisson's ratio. ELFORM 13 is a 1-point constant stress with nodal pressure averaging technique used to alleviate volumetric locking. This element formulation is suitable for materials with Poisson's ratio greater than '0' [18]. Quadratic 8-noded hexahedron (ELFORM 3) and quadratic 4-noded tetrahedron (ELFORM4) with nodal rotations are accurate for small strains and tend to lock volumetrically. Higher order tetrahedral elements (ELFORM 16 and 17) and meshless methods (ELFORM 41, 42 and 43) are not evaluated in this study.

GEOMETRY AND BOUNDARY CONDITIONS

Figure 3 shows the geometries employed for carrying out the compression simulations. The geometry represents a cylindrical foam specimen of 130mm diameter and 80mm thick; the thickness is chosen to be consistent with the typical thickness employed in testing of PU foams. As 'element formulation' is one of the parameters being evaluated, the foam specimen geometry is discretized using both hexahedral (Figure 3a) and tetrahedral (Figure 3b) elements. Element size is fixed at 10mm, resulting in eight elements along the thickness of the foam. This element size is chosen based on the typical sizes of elements employed for discretizing foam components in subsystem and vehicle level simulations. The bottom nodes of the specimen geometry are fully constrained to simulate a rigid substrate. Compression is modeled using movement of a compression platen coming into contact with the top nodes of the foam specimen. The compression platen is modeled in two ways, as a rigid wall and as a

deformable flat cylinder with elastic material properties of steel. Representing the compression platen as a rigid wall does not require an explicit contact definition between the platen and the specimen. Also, the parameter FRIC that defines a Coulomb friction coefficient is set to '0' representing a frictionless sliding after contact. This models a realistic unloading behavior where the foam is not subjected to a tensile loading by the compression platen. A surface-to-surface contact had to be defined in the case when the compression platen was modeled as a deformable cylinder. Friction parameters (FS, FD and DC) in the contact formulation were set to '0'.

ELEMENT FORMULATION DOE AND MATERIAL MODEL PARAMETER SETTINGS

Three hexahedral element formulations (ELFORM -1, 1, and 2) and two tetrahedral element formulations (ELFORM 10 and 13) are chosen for further evaluation in the context of foam simulations, as explained in an earlier section. Hourglass control was employed to avoid the hourglass modes when using ELFORM 1. Three settings of the parameter IHQ, which controls hourglass, were evaluated: 3, 5, and 6. Hourglass coefficient (QH) is set to the default value of 0.1, for IHQ = 3 and 5 and to 1.0 for IHQ = 6.

For each of these settings of ELFORM, the compressive rate-dependent loading and unloading behavior of the foam is simulated at five different engineering strain rates, as shown in Table 1. Three of these chosen simulation strain rates are the same as strain rates at which compressive stress-strain information is available from experiments (Figure 4). Two additional simulation strain rates (0.01505/ms and 0.064/ms) are chosen to assess the accuracy of interpolation obtained with various ELFORM settings.

For all simulations in the Design of Experiments (DoE), mass scaling is employed by setting the parameter DT2MS that controls time step to -1E-4 which is in the order of the values used in the vehicle level or sub-system level simulations. Since the chosen material model is rate dependent, the option of using time scaling is unavailable. The flags in the Fu-Chang Foam material model are set as explained below:

- SFLAG - set to '1', as the input stress-strain response at various strain rates is generated from a velocity controlled test yielding a constant "engineering" strain rate
- SRAF - set to '0' to calculate elemental strain rates using a running weighted averaging technique. Numerical instabilities are observed when SRAF is set to '1'.
- TFLAG - set to '0' resulting in a rate dependent linear tensile behavior governed by the initial slope of the compressive stress-strain information at a corresponding strain rate.
- RFLAG - set to '1' resulting in evaluation of elemental strain rate based on strain rates in each principal direction