Finite Element Modelling of the Mechanics of Solid Foam Materials

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Veniet tempus quo posteri nostri tam aperta nos nescisse mirentur.

(The time will come, when our ancestors will wonder why we did not know such obvious things.)

Lucius Annaeus Seneca
Roman Statesman, philosopher
Preface

The work presented in this doctoral thesis has been carried out at the Department of Aeronautical and Vehicle Engineering, School of Engineering Sciences, Kungliga Tekniska Högskolan (KTH). Financial support was kindly granted by the Swedish Research Council (Vetenskapsrådet) and in part by the European Commission, within the Fifth RTD Framework Programme.

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Stefan must be given credit for encouraging me whenever I came from the testing lab, face hanging and claiming that all tests failed, since the specimens “just broke”. I admired his endurance and his never failing attempts to read my reports and to find the actual meaning in my words when I again had handed him a few pages filled with some seven mile-long, hard to understand sentences, being a combination of several thoughts in multiple subordinate clauses, assuming that it was the most concise and best to understand form of explaining that complicated things could be grasped instantly if neatly wrapped in a cascade of words, some commas and a trailing period. I appreciate his work which certainly helped to improve the quality of my papers.

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Finally, words of thank go to my dear Susanne who supported me with all her love and understanding, to my parents, and last not least to the Osquars.

Stockholm, March 2005

[Signature]
Abstract

Failure of bi-material interfaces is studied with the aim to quantify the influence of the induced stress concentrations on the strength of the interfaces. A simple point-stress criterion, used in conjunction with finite element calculations, is evaluated to provide strength predictions for bi-material bonded joints and inserts in polymer foam. The influence of local stress concentrations on the initiation of fracture at open and closed wedge bi-material interfaces is investigated. The joint combinations are analysed numerically and the strength predictions obtained from the point-stress criterion are verified in experiments.

The predictions are made using a simple point-stress criterion in combination with highly accurate finite element calculations. The point-stress criterion was known from earlier work to give accurate predictions of failure at cracks and notches but had to be slightly modified to become applicable for the studied configurations. The criterion shows to be generally applicable to the bi-material interfaces studied herein. Sensible predictions for the tendentious strength behaviour are made with reasonable accuracy, including the prediction of crossover from local, joint-induced failure to global failure.

To study the micromechanical properties of a cellular solid with arbitrary topology, various models of a closed-cell foam are created on the basis of random Voronoi tessellations. The foam models are analysed using the finite element method and the effective elastic properties of the model cellular solids are determined. The calculated moduli are compared to the properties of a real reference foam and the numerical results show to be in very good agreement.

The mechanical properties of closed-cell, low-density cellular solids are governed by the stiffnesses of the cell edges and the cell faces. Idealised foam models with planar cell faces, cannot account for the curved faces found in some metal and polymer foams. Finite element models of closed-cell foams are created to analyse the influence of cell face curvature on the stiffness of the foam. By determining the elastic modulus for foams with non-planar cell faces, the effect of cell face curvature can be analysed as a function of the relative density and the distribution of solid material between cell edges and faces.

Foam models are generated from disturbed point distribution lattices and compared to models obtained from random distributions. The aim is to analyse if and how the geometry of the cells and their spatial arrangement influences the mechanical properties of a foam. The results suggest that the spatial arrangement and the geometry of the cells have significant influence on the properties of a foam. The elastic properties calculated for models from disturbed foam structures underestimate the elastic moduli of the foam, whereas models from random structures provide results which were in very good agreement with a reference foam.
Dissertation

This thesis consists of a brief introduction to the area of research and the following appended papers:

**Paper A**

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**Paper B**

*submitted for publication*

**Paper C**

*submitted for publication*

**Paper D**

*submitted for publication*

**Paper E**

*submitted for publication*

Papers A and B were in part presented in: S. Ribeiro-Ayeh: *On the Bi-Material Interface Strength of Inserts in Polymer Foam* in *Proceedings of the Sixth International Conference on Sandwich Structures*, Ft.Lauderdale, Florida, USA, 2003

Division of work between the authors

Paper A
Ribeiro-Ayeh performed the experiments, the finite element analyses and wrote the paper. Hallström initiated and guided the work and contributed to the paper with valuable comments and revisions.

Paper B
Ribeiro-Ayeh performed the experiments, the finite element analyses and wrote the paper. Hallström initiated and guided the work and supplied valuable comments and revisions to the paper.

Paper C
Ribeiro-Ayeh developed the foam models, performed the finite element analyses and wrote the paper. Hallström initiated and supported the work and supplied valuable comments and revisions to the paper.

Paper D
Ribeiro-Ayeh developed the foam models, performed the finite element analyses and wrote the paper. Hallström supplied valuable contributions to the interpretation of the results, and the content and structure of the paper.
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1. Introduction

The sandwich concept is a widespread technique for achieving stiff and strong structures while maintaining a low structure weight. It is utilised in numerous applications for example in the vehicle, transportation and building sectors.

In commercial aircraft, sandwich design is well established mainly in cabin interiors, hatches, doors and various control surfaces, but even large structures such as cabin floor panels or fuselage parts may be produced in sandwich design (Fig. 1). Carbon fibre sandwich panels offer high structural stiffness and superior thermal properties and are commonly used in aerospace launch vehicles and satellite structures, both in interior and exterior structures (Fig. 2).

![Figure 1: Airbus A380 aircraft](Airbus) ![Figure 2: Ariane 5 heavy-lift launcher](European Space Agency)

For railway vehicles, interior modules such as partition walls, ceiling, luggage racks, floor panels or the whole of the car body may be built in sandwich design (Fig. 3). The construction industry makes use of sandwich panels for the lightweight design of large structures, such as the Stockholm Globe Arena, shown in figure 4.

![Figure 3: Gardermoen high-speed train](Adtranz ABB Strommens) ![Figure 4: Stockholm Globe Arena](Stockholm Globe Arenas)

Ongoing active development continues on the field of sandwich structures and the question of load introduction is a remaining and recurring challenge for designers and engineers. As of today, the difficulties encountered with load introductions are
frequently approached as isolated problems and not integrated in the overall design process at an as early stage as one could wish. The premiere reason for this is the lack of reference cases and documented knowledge in terms of systematic, analytical methods for the design of these load introductions. In consequence, considerable weight may be added to structures as a result of inferior design; both through extra material (such as denser cores, thicker faces, larger inserts and more adhesives) but also due to low allowable design loads and cautiously high safety factors to compensate for poor efficiency and reliability. Thus, the design of inserts is oftentimes less than optimal and stands in sharp contrast to the substantial weight savings that can be achieved by means of advanced sandwich design and improved manufacturing methods.

2. **Strength analysis**

A sandwich construction is an inhomogeneous compound of very specialised, overall high but locally low performance materials. Sandwich plates with commonly used transversely flexible core materials, such as cellular foams or honeycombs lack the necessary stiffness and strength to sustain localised loads. Therefore, load introduction into such a sandwich structure relies on the integration of adequately designed transition media, commonly referred to as inserts (Fig. 5). The purpose of an insert is to distribute localised loads in the panel in an appropriate manner [1]. The core

![Image](Figure 5: Aluminium insert in a sandwich beam [2])

is often replaced locally by a more high-performing material, such as foam of higher density or by composite or metal inserts which provide sufficient local strength and can accommodate mechanical fasteners for the transfer of external loads into the sandwich structure.

2.1. **Failure assessment**

The material properties, the mechanical sandwich properties and the insert geometry are the foremost factors determining the load bearing capabilities of an insert. Comprehensive formulas for the design and dimensioning of load introductions and inserts have yet to be developed. For specific design cases, such as some space vehicles, handbooks presenting design charts and formulae for inserts exist. Here the capabilities of inserts are determined by utilisation of measured material properties.
in combination with experimentally verified analytical models. These may be used for preliminary design but they may then need to be substantiated by testing of the actual configuration [3, 4].

(a) internal metal doubler [5]  
(b) Hour-glass shaped insert [6]

Figure 6: Examples of failure near inserts

The use of local reinforcements creates an assembly of materials of different stiffness, with differences in elastic constants and mode of deformation. Structural failure is oftentimes observed near or at an insert (Fig. 6). The existence of multi-material corners of dissimilar material and challenging local geometries are believed to determine the stress field in the region closest to the insert. Due to geometric and/or material mismatch, areas of high local stress may be observed at these locations [7]. The local stress fields could in part be described by use of fracture mechanics terms, yet they are set aside in many analyses [8, 9, 10] and only a limited number of attempts to actually characterise the stress fields in the immediate vicinity of an insert exists.

The local stress fields are believed to contribute substantially to the initiation of fracture and material failure and should therefore be given special consideration when estimating the load bearing capabilities of a structure [11]. Analytical approaches [12, 13] and numerical solution routines [14, 15] have been derived for specific material combinations and geometries, but the analysis of practical problems often requires a combined approach of both analytical and numerical descriptions [16].

**Failure criteria**

A more general approach which may be used within the scope of a detailed finite element analysis is desirable for the analysis of stress fields in the development of load introductions and a stress-based failure criterion is suggested herein. The point-stress criterion, originally proposed by Whitney and Nuismer [17] may provide a tool for the determination of the strength of a brittle material when the maximum stress is highly localised. Independent of the local geometry, the point-stress criterion relates general stress level at a certain distance from a stress concentration to the un-notched strength and the fracture toughness of the material.
The point-stress criterion has been successfully applied for the prediction of failure due to geometric discontinuities in structural PVC foam [18, 19], as well as for failure prediction of specific insert configurations in sandwich plates with material and geometric discontinuities [5, 6].

As it had been utilised in earlier work [18, 19, 20], the point-stress criterion was only applicable locally at stress concentrations, operating on the maximum tensile tangential stress $\sigma_{\phi\phi}$ at a characteristic distance $r_{ch}$ from a notch tip (Fig. 7). A generalisation of the criterion by formulating it to work on the first principal stress $\sigma_{11}$, allowed for the use of the criterion beyond the immediate vicinity of a stress concentration [21]. Then the strength of bi-material interfaces could be analysed, taking material properties and the local geometry into consideration. By establishing a relationship between the failure strength and the geometry of the bi-material interface (Fig. 8) a tool was obtained, which in the future could permit the use of the point-stress criterion for the selection of suitable material pairings and for the design of optimised interface geometries.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure7.png}
\caption{Local geometry at an arbitrary wedge notch [19].}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure8.png}
\caption{Bi-material interface corner}
\end{figure}

2.2. Analysis of bi-material interfaces

The proposed generalisation of the point-stress criterion allowed for its application beyond the immediate vicinity of a stress concentration (Fig. 9). Evaluated within

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure9.png}
\caption{Evaluation of the point-stress criterion (hatched area)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure10.png}
\caption{Fracture near an insert [22]}
\end{figure}

the whole of the test specimens, the criterion could be used to identify failure critical
areas (Fig. 10) and to estimate the corresponding failure load.

In the case of bi-material beams, it showed to be possible to obtain numerical estimates of the failure strength which were in very good agreement with experimental data. Furthermore, a transition between different modes of failure could be identified, which could confirm the usability of the point-stress criterion as a local criterion in the vicinity of a stress concentration as well as globally in the whole of the test specimens.

In the analysis of aluminium inserts embedded in Rohacell® foam [23], where multiple stress concentrations were present, the point-stress criterion could be used to successfully identify the failure critical areas. Estimates of the failure strength were conservative and in reasonable agreement with experimental results.

Figures 11 and 12 show the experimental analysis of inserts and of bi-material beams respectively. The fracture locations clearly differ, depending on the existence and location of a failure critical stress concentration. The large fracture surface which does not reveal the lower corner of the insert (Fig. 11(a)) and the fracture
location distant from the bi-material interface (Fig. 11(b)) suggest, that for these geometries failure was probably not due to local stress concentrations. Fracture near the critical lower corner of the insert (Fig. 12(a)) and near the bi-material interface (Fig. 12(b)) on the other hand, may lead to the conclusion that the existence of high local stresses may have played a role.

In correspondence with the experiments, the numerical predictions captured the relationship between interface angle or insert geometry and failure load.

3. Stiffness analysis

A foam consists of gas cells or bubbles in a liquid medium, separated by thin films the cell walls or cell faces. Depending on their size and gas pressure, the cells may be approximately spherical (wet foam or soap froth) or form polyhedra (dry foam or cellular solid). In the current analysis, the latter kind of foams are considered as they can be found for example in the aforementioned engineering applications.
Since the technical properties of these dry foams are comparable to the properties of a solid material with voids, the foams are also referred to as cellular solids.

In the stiffness analysis of cellular solids, the description of the material is shifted from a macroscopical point of view, where the material was treated as a continuum solid to a microscopical approach, taking into account the structural complexity of the foam. In figure 13 examples are given of the variety of microstructures found in different cellular solids. It is evident that the foams are irregular structures, consisting of a network of interconnected cells of individual sizes and geometries.

The mechanical properties, such as strength and modulus, of cellular solids are largely determined by the geometrical features of the material and by the properties of the solid material from which the foam is made [24].

### 3.1. Previous analytical and numerical models

The mechanical properties of cellular solids may be determined experimentally on the microscale level [25], but advanced specimen preparation is required [26] and the results may be influenced by local inhomogeneities of the material.

Gibson and Ashby [24] developed analytical foam models based on an idealised single cell geometry, well suitable for the description of open- and closed-cell foams. Despite their simplicity, they offer a good representation of the cell mechanics and were successfully used for the derivation of various scaling laws for the properties of cellular solids [24].

![Foam model of monodisperse tetrakaidecahedral cells](image1)

![Beam model of a random open-cell foam](image2)

Micro-mechanical models of open- and closed-cell foam may be created on the basis of originally ordered lattice structures. Examples of such are periodic Kelvin foam structures (Fig. 14) which were examined in ordered and in randomised versions by various authors [27, 28]. Finite element simulations of various types of open-cell foams (Fig. 15) may be made by modelling the cell edges as beams [27, 29, 30]. For
periodic, repeating structures of geometric regularity, the analysis may be simplified by using partial models of foam cells [27, 31, 32].

Other modelling techniques in which a representation is sought which closely resembles the microstructure of a real cellular solid may be the use of tomographic images, digitised images [33, 34], or x-ray scans [35, 36] of a foam. While being a close digital reproduction of the structure of a real foam, these models are unique for each individual foam sample and may not necessarily be representative. Generally, digitised models are not periodic, which may hamper the application of boundary conditions in finite element models.

The mechanical properties of the model foam may depend on the digitising process and the obtained resolution of the model [37]. A coarse resolution may introduce numerical errors to the FE analysis which could be avoided by including a high level of detail in the digitising but then it may not always be possible to create a finite element model from the data as the model may be very large [38].

3.2. Cell growth - Voronoi structure

Models of cellular solids may be generated by means of Voronoi tessellation of dis-

![Figure 16: Two-dimensional cell growth simulation](image-url)
tributions of seed points in space. In a Voronoi tessellation, a cell is defined by the
space that is closer to a specific seed point than to any other. Mathematically, the
Voronoi tessellation is obtained by allowing spherical bubbles to grow with uniform
velocity from each of the seed points (Fig. 16). Wherever the bubbles touch, growth
is halted at the contact surface, but allowed to continue elsewhere (Figs. 16(b)–
16(e)). In this respect the tessellation is similar to the actual process of liquid foam
formation [39].

The amount of structure or disorder in the Voronoi tessellation depends on the
spatial distribution of the seed points. If they are arranged in regular arrays or grids,
models of ordered foams may result (Fig. 14). Seed points in a Poisson distribution,
randomised lattice arrangements or seeds deployed by random sequential adsorption
(RSA) algorithm [40, 41] may result in unstructured, random Voronoi tessellations.
The seed distribution influences the cell morphology, the spatial disposition of the
cells, and the cell size distribution (Fig. 17).

3.3. Finite element modelling

The micro-mechanical foam model was prepared as a spatially periodic model built
from a cubic unit element of foam, a so called “representative volume element”
(RVE) or “statistically homogeneous specimen” [42]. Countless identical copies of
the RVE fit together to fill space, forming a space-tiling periodic domain. Each
unit element must be large enough to be statistically representative and it may thus
contain numerous foam cells of different size and shape (Fig. 18).

Finite element (FE) models of open-cell cellular solids may be created by meshing
the cell edges with beam elements (Fig. 15). For the analysis of closed-cell
foams, the cell faces can be meshed with either shells or membrane elements and
reinforcing beam elements must be used along the cell edges. Besides the relative
density, the distribution of solid between cell faces and edges must be taken into account to obtain reasonable stiffness estimates. Models made of shell elements, where all material is located the cell faces may overestimate the properties of polymer foams [27, 30]. The geometry of the beam elements may be simplified to a circular cross section instead of the triangular Plateau border shape. This may lead to a reduction of the principal second moment of area and thus a somewhat lower bending stiffness of the edges with respect to the real material [27]. The stiffness reduction may be negligible in the modelling of closed-cell foams, where the cell faces predominantly contribute to the foam stiffness [43].

3.3.1. Periodic boundary conditions

The use of a parallelepipedal RVE facilitates the application of periodic boundary conditions to the finite element model and can allow for multi-axial loading of the model. The use of periodic boundary conditions implies that the RVE is surrounded by images of itself ad infinitum, meaning that nodes on any pair of boundary surfaces on opposite sides of the RVE have identical opposite displacement components [44, 45].

When denoting a pair of opposite boundary surfaces A and B (Fig. 19), the boundary condition may be stated as \( u_i^A = -u_i^B \) for the displacement vectors \( u_i \) of a node pair. The displacement conditions on the boundaries of the RVE may then be written by specifying the average strain over the volume of the RVE, \( \bar{\varepsilon}_{ij} \), as [46]:

\[
\bar{\varepsilon}_{ij} = \frac{\delta u}{\delta x} = \frac{u_i^B - u_i^A}{x_j^B - x_j^A}
\]  

(1)

For the implementation of the periodic boundary conditions in the FE model (Fig. 20), the mesh on any opposite sides A and B needs to match exactly, which may be achieved by using a mesh generator such as the Cubit [47] where such a condition can be prescribed.
3.3.2. Evaluation of elastic moduli

Series of FE analyses (Fig. 21) allow for the population of the compliance matrix $S$ of each RVE. Subsequently, the elastic properties may be determined by identifying the elements $s_{ij}$ of the compliance matrix. The directional material properties may then be averaged by calculating the effective isotropic properties [49].

In figure 22 the elastic properties of a low-density polymer foam obtained from a series of different FE models are compared to the data for an existing foam, Röhm Rohacell® 51WF. The material properties of the Rohacell® solid material [50] were

![Figure 21: Nodal displacement plots [48]](image1)

(a) Uniaxial tension  
(b) Shear

![Figure 22: Elastic moduli of Rohacell® foam models [48]](image2)

(a) Young’s modulus  
(b) Shear modulus
used in the finite element models and the results were in very good agreement with experimental data [50, 51] and the specifications of the real foam [23].

3.4. Variations of the cell morphology

3.4.1. Topological disorder

The influence of the seed distribution on the cell morphology and the elastic moduli of a model foam may be studied by evaluating and comparing the results for different ordered and disordered seed distributions [52].

![Figure 23: Examples of more or less disturbed Voronoi foam models created from different seed point distributions](image)

To represent the structural disorder in a real foam (Fig. 13), Voronoi tessellations for the modelling of cellular solids may be created from random seed point distributions [53] or from randomised perturbations of initially structured seed lattices [27, 28, 29].

Models created from ordered seed distributions (Figs. 23(a), 14) may be used to mimic the structural disorder of real foams as the randomness in the seed distribution is gradually increased (Fig. 23(b)). The degree of randomness and the corresponding geometric disorder may be described through the definition of a “topological disorder” [53] or “topological energy” [54] which measures the deviation of the individual cell shapes from geometrically symmetric polyhedra. The higher the topological disorder, the less uniform the cells.

In the analysis, Voronoi tessellations based on ordered BCC and FCC seed structures were randomised and compared to foam models created from random RSA seed structures. It was found, that the spatial distribution of the seed points significantly influenced the cell shapes and subsequently affected the mechanical properties of the foam. The calculated elastic moduli of the ordered structures showed a considerable degree of anisotropy and they underestimated both Young’s modulus and shear modulus of the real reference foam [52]. Increased randomness in the initially ordered lattices resulted in more isotropic properties and a better estimate of the elastic
moduli, but it was accompanied by a significant increase in cell face area. Densely packed RSA point distributions on the other hand provided models of random cell structures, which appeared to be the most suitable representation of a cellular solid (Fig. 23(c)).

### 3.4.2. Non-planar cell faces

The gas pressure between adjacent cells and the production process may affect the shape of the cell faces. In an ideal, dry foam the cell faces are planar, which may not be the case for a real foam (Fig. 13). Especially in the case of aluminium foams (Fig. 13(d)) it is believed that the stiffness of the foam can be reduced by curved or corrugated cell faces [32, 55, 56].

![Figure 24: Foam with non-planar cell faces [57]](image)

In order to investigate the influence on the elastic moduli of the foam, an analysis was performed where the cell faces were given different curvatures (Fig. 24) by means of Schwarz-Christoffel mapping [58], allowing for an arbitrary definition of an out-of-plane shape of the cell faces.

The results showed, that the stiffness of the foam may be significantly influenced by the shape of the cell faces [57], which was in accordance with related studies on open-cell foams [59]. It was found, that the elastic moduli were considerably lower when the cell faces were non-planar. The lower the distribution of solid and the more material in the cell faces, the greater was the reducing effect of the cell face curvature. While thickness variations of the cell faces alone may cause a decrease in shear and bulk moduli [60], it was also specifically shown that the observed reduction in stiffness was due to the face curvature and not only due to the reduction of face thickness associated with the imposed curvature.
3.4.3. Distorted cells

In some foams, the cell shapes may exhibit a substantial deviation from idealised spherical bubbles (Fig. 13(c)). This distortion of the cells, which may be caused by the foam production process can cause unwanted anisotropic properties of the foam [61].

Different variations of the cell geometry may be analysed by creating foam models of differently distorted cells. The seed point distribution within a RVE may be influenced such that the cells of the foam are of different shape, creating a foam with controlled anisotropic properties. Figure 25(a) shows a models with cells which were elongated to an aspect ratio of [8:1:1] giving them almost cylindrical shapes with a height of eight times the diameter. In the same manner cells may be given a disc-like appearance such as in the model in figure 25(b) where the cells have an aspect ratio of [1:5:5], meaning the diameter is five times the cell height.

Ongoing research suggests, that the cell shapes might have a profound effect on the elastic moduli of the foam [62].

4. Future work

Possible further research could include a revision of the point-stress criterion and to improve it to better match experimental results. This might be accompanied by a modification of the criterion to the analysis of multi-axial stress states.

For the analysis of inserts in sandwich structures it would be of great interest to extend the point-stress criterion and to investigate tri-material interfaces, such as the junction between sandwich face, core and insert.
In the area of micromechanical modelling of cellular solids, it would be a fascinating challenge to use the models for simulations in the field of fracture mechanics (Fig. 26). This could involve the investigation of crack growth and the analysis of fracture paths in the foam. Of interest could be the investigation of the shape of the crack front and the progress of fracture through the material, which could be either through the cell faces or along the cell edges. Considering the use of the point-stress criterion, it would be very interesting to possibly establish a link between fracture on the cell-level and failure of the cellular solid on a macroscopic scale.

Considering the mechanics of cellular solids and their use in and as crash absorbing structures it would be appealing to simulate the crushing of a foam on a micromechanical level (Fig. 27). The transition from elastic deformation to the onset of failure by cell wall buckling, the plateau phase and the progressing densification of the foam could be simulated.

The analysis of local defects in the foam might be of interest for practical applications and for the production of foams. One could for example analyse the mechanics of partially closed-cell foams by including the effects of missing cell walls. The influence of unwanted large gas bubbles, as they might occur in the foam production process could be investigated.

Lastly, the presented micromechanical models might very well be used to tailor new foams by demand. Thus, one could determine the required properties, such as cell size and solid material according to the desired elastic properties of the foam.
Bibliography


Fe Modelling of the Mechanics of Solid Foam Materials


