Honeycomb Modeling for Side Impact Moving Deformable Barrier (MDB)

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Abstract

Usually honeycomb is used as an energy absorber under impact loads. LS-DYNA constitutive model MAT-26 (*MAT_HONEYCOMB) is to mathematically model honeycomb as an energy absorber. The NHTSA MDB is a physical model of a typical impacting vehicle in side impact tests. The frontal part of MDB is made of honeycomb not just as an energy absorber but as a physical model of a typical car front end. Therefore, here the use of MAT-26 has some particularities, which are described in the paper. The MBD LS-DYNA model has been successfully used at GM for the last ten years.

Key Words: Cells' Air, Side Impact Barrier, Cellular Structure, Honeycomb, and Material-26

Abbreviations: GM, FEM, LCMB, LS-DYNA, MDB, MAT-26, and NHTSA.

Objective, Introduction and Approach

The objective of this paper is to share with LS-DYNA users the experience of using constitutive model MAT-26 in the aluminum honeycomb modeling in a particular application. The application here is the finite element model (FEM) of Moving Deformable Barrier (MDB). The main objects of the paper are MAT-26 and honeycomb, not MDB.

The successful use of MAT-26 constitutive model in the application has involved MAT-26 implementation in LS-DYNA and special static and impact tests and studies. Neither a detailed description of the test methodology nor numerical results and data are presented in the paper. Such detailed description would require several papers. Instead, some graphical information, descriptions and formulas are presented to just illustrate and help to explain the use of MAT-26 in this particular application.

The particularities of honeycomb performance under static and impact loads have been studied. Honeycomb is a cellular structure, not a material. Honeycomb, as material is a usual assumption in tests and analyses. Due to this assumption, the explanations of the honeycomb performance differences under static and impact loads are based on the strain-rate and test-sample size effects. Based on the studies described in this paper, different explanations of the performance differences are presented below.

The approach used here is to model honeycomb (in a cost and computer-time efficient way) as a material, while making the necessary for particular application adjustments to account for the honeycomb performance, as a cellular structure. In the MDB FEM application, the adjustment is to use in the input the stress-strain curve from appropriate tests.

Aluminum Honeycomb

Honeycomb is not a material, but a thin-walled cellular structure, Fig. 1, made from different types of materials. The so-called “expansion” process is usually used to produce aluminum honeycomb. In this process adhesive has been added on aluminum sheets along the lines parallel to the T-direction. The sheets are then assembled and cured in a block. Then the slices (aluminum sheets) of the block are expanded to the desired (hexagonal) cell cross section configuration. The corrugated process (in which pre-corrugated aluminum sheets are stacked and adhesive bonded into blocks) is used for high-density honeycomb. The parallel to each other cells run between two parallel sides of a block, and are open on these block sides.

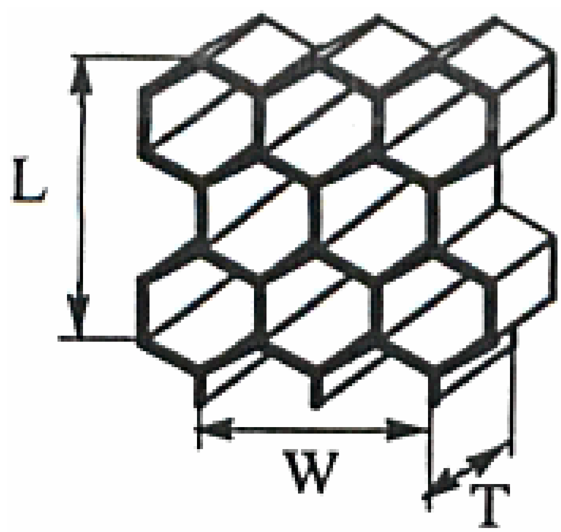

Fig.1. Aluminum honeycombs cellular structure.

Its manufactures as material properties present the properties of honeycomb, and refer to honeycomb as honeycomb material [1]. To obtain the material-like properties, samples of honeycomb are tested under compression loads in the T-direction, Fig.1, and on shear loads in the (T, W) and (T, L)-directions. From the tests, load-deflection curves, [1,2], are defined, Fig.2: compressive stabilized and bare strength/force (strength), shear force, compressive and shear moduli. The stabilized strength is the ultimate force from the test in which the sample cell edges are stabilized by being adhesive bounded to the testing machine facings. The bare force is from the test without stabilizing the cell edges.

Honeycomb stresses are computed as the test forces over the correspondent cross sectional areas of the sample, not over the cross sections of the aluminum sheets forming the sample cells. From the beginning slopes of the test stress-strain curves, the moduli are computed. The honeycomb density is computed as mass over the sample volume, not over volume of aluminum sheets. Therefore the honeycomb density is significantly lower than the density of aluminum. Under compression forces the honeycomb density increases significantly.

Honeycomb, as material, may be qualified as elastic perfectly plastic material undergoing very large deformations. It crushes mostly under almost constant predictable force/stress level. Therefore it is considered to be a perfect energy absorber. According to the known information, honeycomb is used mostly for energy absorbing purposes in different applications.

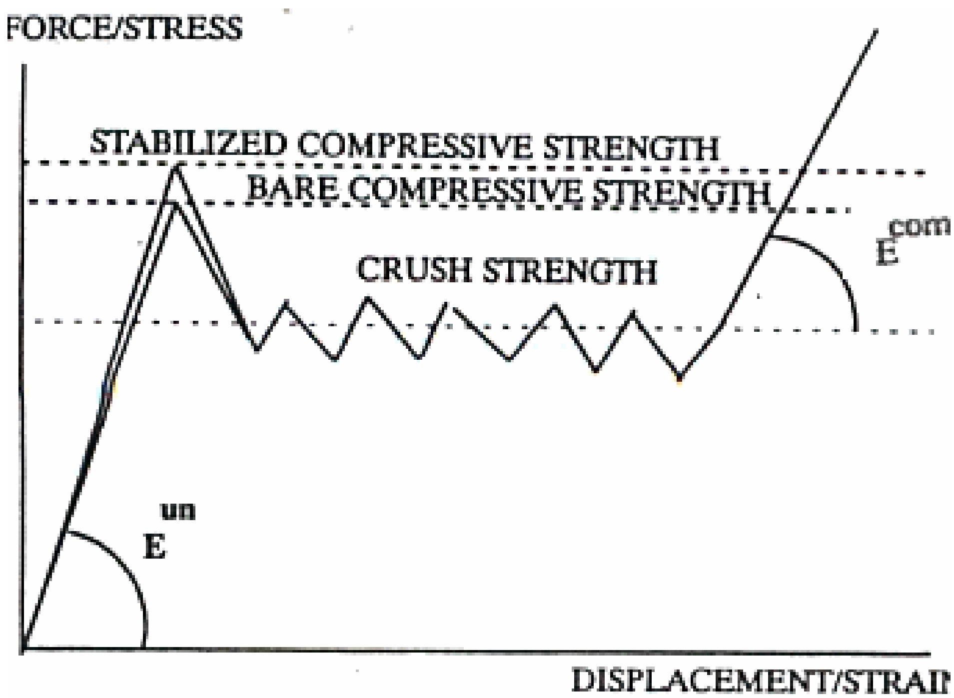

Fig.2. Honeycomb material properties.

At Hexcel [3], honeycomb tests are conducted mostly under static (test velocity 25.4 mm/min) loads. Some dynamic tests (test velocity 6-8m/sec) show the stresses increase (comparing with static test) by 20 to 30%. In [4], there is information from other reference that honeycomb forces do not depend on impact velocities below 30m/sec. The test results in [4], however, show that under impact velocities up to 15m/sec there is a predictable crush force increase up to 20%. There is indication that in impact tests the specimen size also affects the test results. According to [5], at impact velocity up to 13m/sec no effect on high-density honeycomb crush force was found. However, for low-density honeycomb a 10% of crush force increase was found due to strain rate effect. That and the information from some other publications on honeycomb “material” look controversial.

LS-DYNA Honeycomb Constitutive Model

Following its manufactures honeycomb is considered in LS-DYNA as a material. The detailed description of constitutive model MAT-26 (*MAT_HOHEYCOMB) for honeycomb as a material could be found in [6] and [7]. Back in the late 1980th, while then helping in the MDB FEM development Dr. Hallquist implemented Mat-26 in LS-DYNA as a very simple constitutive model. It was applicable only to a very simple “one-element” FEM. While continue helping, Dr. Hallquist had made improvements in the MAT-26 LS-DYNA code, which had made it possible to use MAT-26 in complex FEM. Those included improvements in MAT-26 formulation, introducing global coordinate system in addition to used to be only local one, more efficient time step algorithm, etc. Here, only some necessary to the topic information on MAT-26 will be presented.

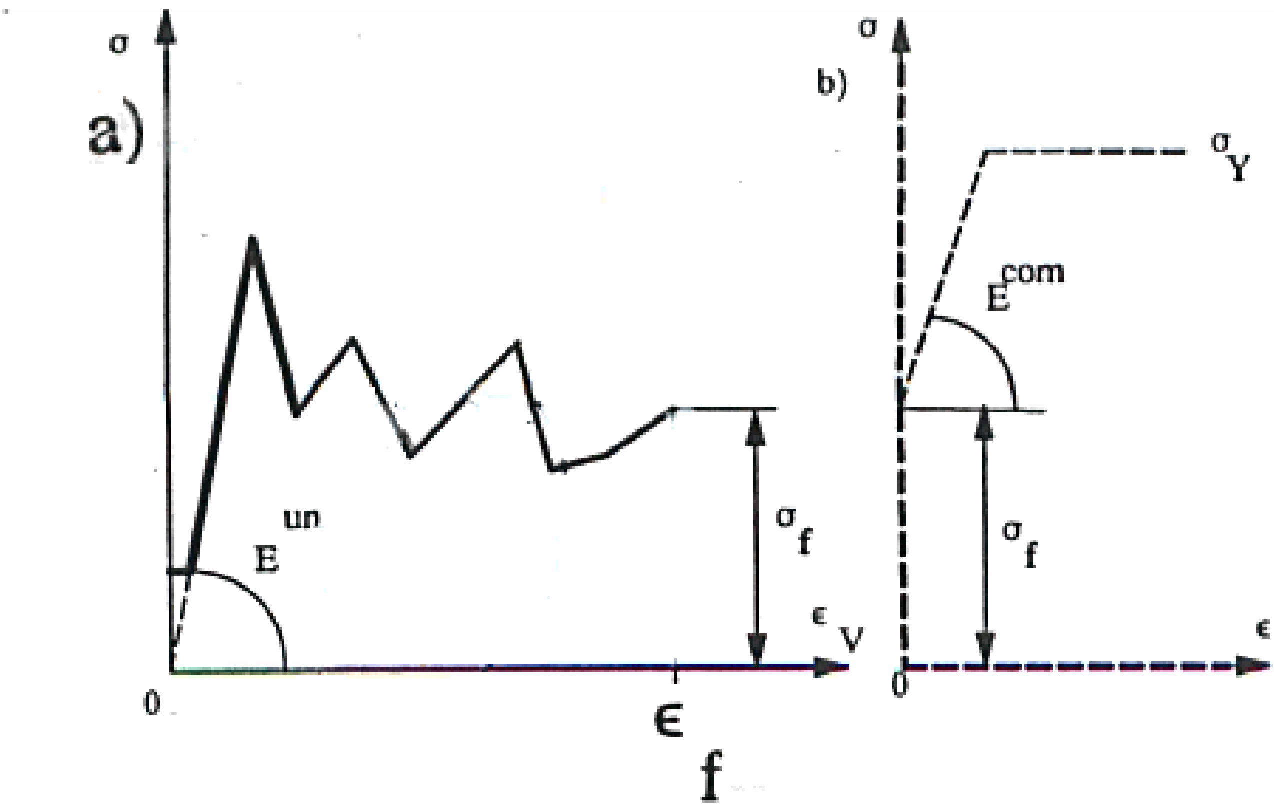

Fig.3. MAT-26 phases: a) not compacted, b) compacted.

The mathematical formulation of MAT-26 comprises of two almost independent deformation phases, Fig. 3. The first, Fig. 3a, is referred to as not compacted phase. In this phase, stresses and strains are uncoupled in all three directions, and each brick finite element is treated as six independent (three compressions and three shears) one-dimensional elements. The second, Fig.3b, is referred to as fully compacted phase. The second stage is in essence a computational means to preclude the size of a brick finite element become equal to zero.

The stresses in the not compacted phase are functions of a brick element relative volume V or volumetric strain ε_v

$$\varepsilon_v = 1 - V, \;\; V = \frac{v}{v_f}, \;\; \varepsilon_f = 1 - V_f, \qquad (1)$$

where: v is the element volume, v_f is the volume of fully compacted element, and V_f is the relative volume of fully compacted brick element.

The compression and shear moduli in the not compacted phase vary from their initial values to values in the fully compacted phase.

$$E_{ii} = E_{ii}^{un} + \beta\left(E^{com} - E_{ii}^{un}\right),\; G_{ij} = G_{ij}^{un} + \beta\left(\frac{E^{com}}{2(1+\mu)} - G_{ij}^{un}\right), \tag{2}$$

where: E^{com} is the compression modulus in the fully compacted phase, E_{ii}^{un} and G_{ij}^{un} are the compression and shear moduli in the not compacted phase, μ is Poisson's ratio, and β is computed from the following expression

$$\beta = \max\left[\min\left(\frac{1-V}{1-V_f},1\right),0\right]. \tag{3}$$

The stresses in the not compacted phase are updated using the experimental stress-volumetric strain/relative volume curves, Fig. 4, and following trial stresses

$$\sigma_{ii}^{n+1^{trial}} = \sigma_{ii}^{n} + E_{ii}\Delta\varepsilon_{ii}, \quad \sigma_{ij}^{n+1^{trial}} = \sigma_{ij}^{n} + 2G_{ij}\Delta\varepsilon_{ij}, \tag{4}$$

where: $\Delta\varepsilon_{ij}$ is the strain increment, n is the time increment.

In the fully compacted phase, honeycomb is an elastic-perfectly plastic material, and its stresses s_{ij} updated as follow

$$s_{ij}^{n+1^{trial}} = s_{ij}^{n} + 2G\Delta\varepsilon_{ij}^{dev^{n+0.5}}. \tag{5}$$

where: $\Delta\varepsilon_{ij}^{dev}$ is the deviatoric strain increment, *n* is the time increment.

In the MAT-26, input experimental l curves like in Fig. 2 are used. From them modulus E^{com} could be computed. Usually the value of E^{com} is significantly lesser than Young's modulus of solid aluminum. Modulus E^{com} has two-fold role in the MAT-26 algorithm. It is used to compute a stable time step, and in the iterations, when selecting the needed stresses, Eq. 4 and 5, from the curves, like Fig.2, 3 and 6. In both cases the value of E^{com} must be significantly larger than the value from the honeycomb tests. Depending on a particular simulation E^{com} should be taken equal to Young's modulus of aluminum or even of steel.

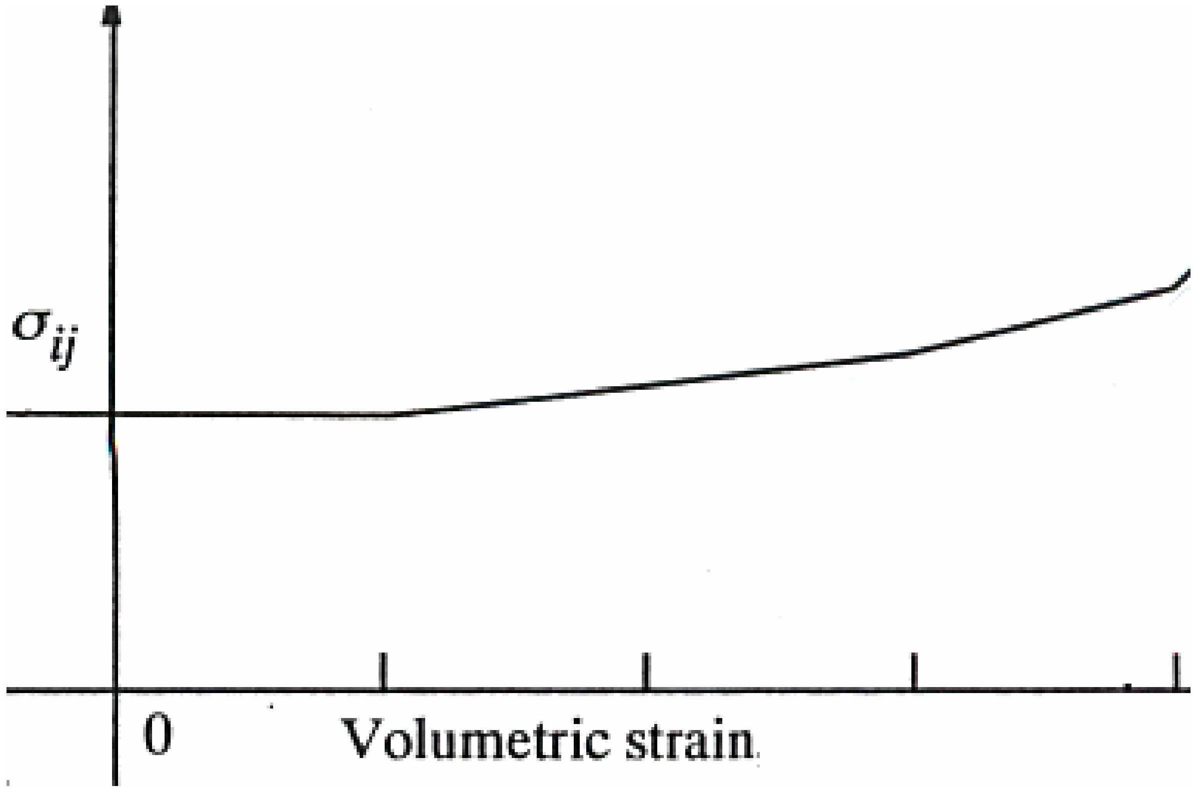

Fig.4. MAT-26 stress-strain input curve.

Moving Deformable Barrier (MDB)

National Highway Traffic Safety Administration (NHTSA) and Dynamic Science Inc. [8] have developed MDB, Fig.5, as a physical model of a typical impacting vehicle in side impact tests. With MDB, it is possible to conduct side impact tests using standard unified methodology consistent with the Rule [9].

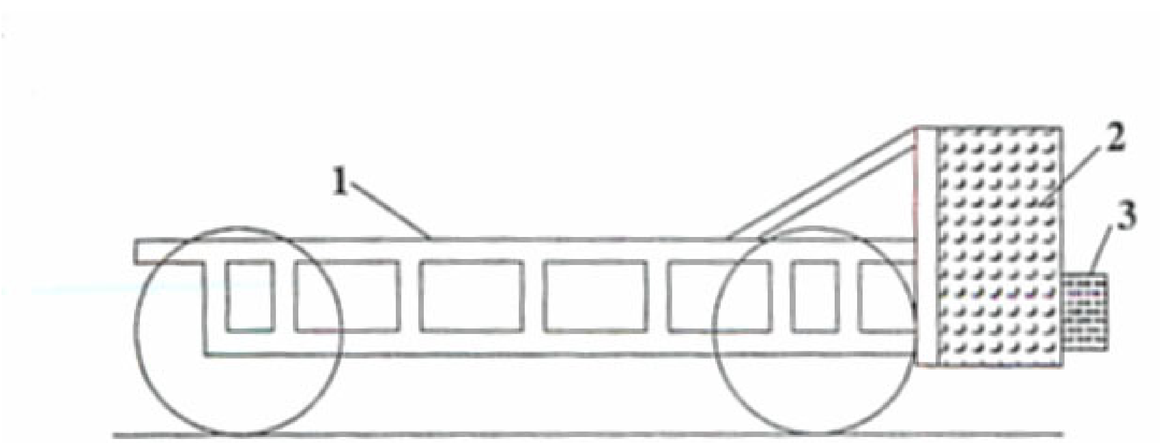

Fig.5. NHTSA Moving Deformable Barrier (MDB)
1)Concept Rigid Frame
2) Honeycomb (Deformable Block) 45psi,
3) Honeycomb (“Bumper”) 245psi.

The MDB development is based on numbers of special and available tests and research. Car-to-LSMB (Load Cell Moving Barrier) impact tests [8] had been conducted to define car front-end properties. LCMB is a special vehicle, having on its flat front-end 32 load cells. Car-to-Car side impact test had also been conducted to study the interaction between the target and bullet cars.

The MDB front end has been specially designed, Fig.5, to be a physical model of a bullet-car front end. The principal parts of the MDB front end are low-density 45psi honeycomb ("front-end body") and high-density 245psi honeycomb ("bumper"). The main objective of using honeycomb is not just to absorb the impact energy, but to generate a physical model of the bullet car front-end. In order to confirm the model, special MDB-to-LCMB and MDB-to-Car impact tests have been conducted. At GM, MDB has been built based on the NHTSA drawings, and then MDB-to-Car tests are conducted to verify the barrier.

Honeycomb and MDB Tests

Detailed tests of honeycomb samples and MDB have been conducted at GM during the development of the MDB FEM to better understand the honeycomb performance in MDB, and to generate experimental data to validate constitutive model Mat-26 for this particular application. That has been necessary due to the lack impact test information for honeycomb 45psi and 245psi used in MDB, and the controversy in the explanation of differences in static and impact honeycomb test results.

Experimental static and impact/dynamic tests of honeycomb samples have included compressive tests in all three (T, L, W), Fig. 1, directions, and shear tests in the T-L and T-W directions. Dynamic tests have been conducted on Drop Silo test machine where honeycomb samples have been impacted by a dropping Drop Silo head.

Following the Rule [9], two types (at 90° and 27°) of dynamic/impact MDB-to-Skateboard vehicle tests have been conducted. The skateboard has been instrumented with load sells similar to the LCMB [8], (but with lesser amount of load cells).

Honeycomb sample stress-strain curves from Drop Silo and static tests in the T-direction are depicted in Fig. 6. Note that the stresses from the static tests are lower than the stresses from the impact tests. Both static and impact stress-strain curves have been used to simulate using LS-DYNA the MDB-to-Skateboard impact tests. In Fig. 7 and 8 depicted are both the experimental and analytical force-time curves from the 90° test and simulation.

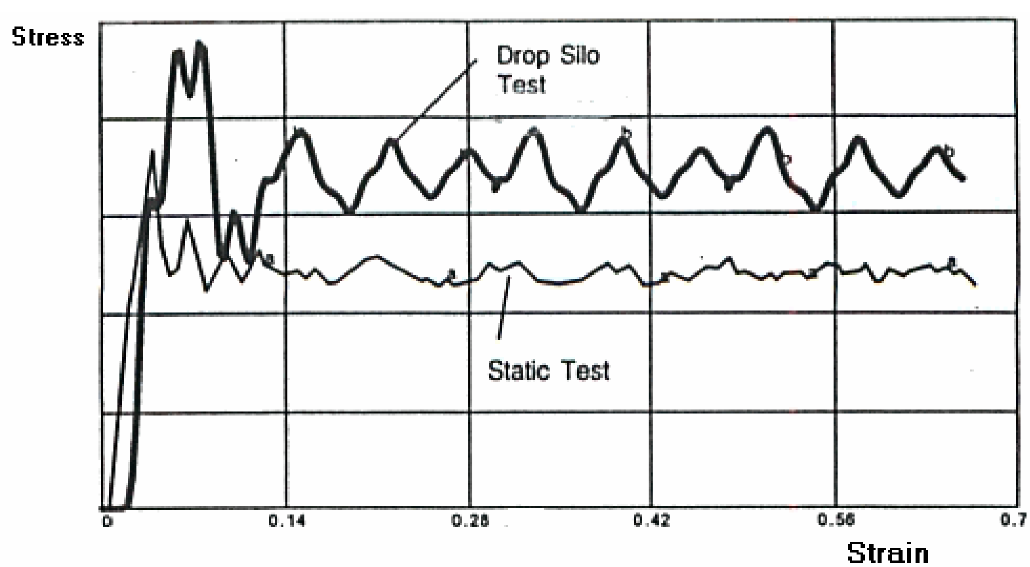

Fig.6. Aluminum honeycomb impact and static test curves.

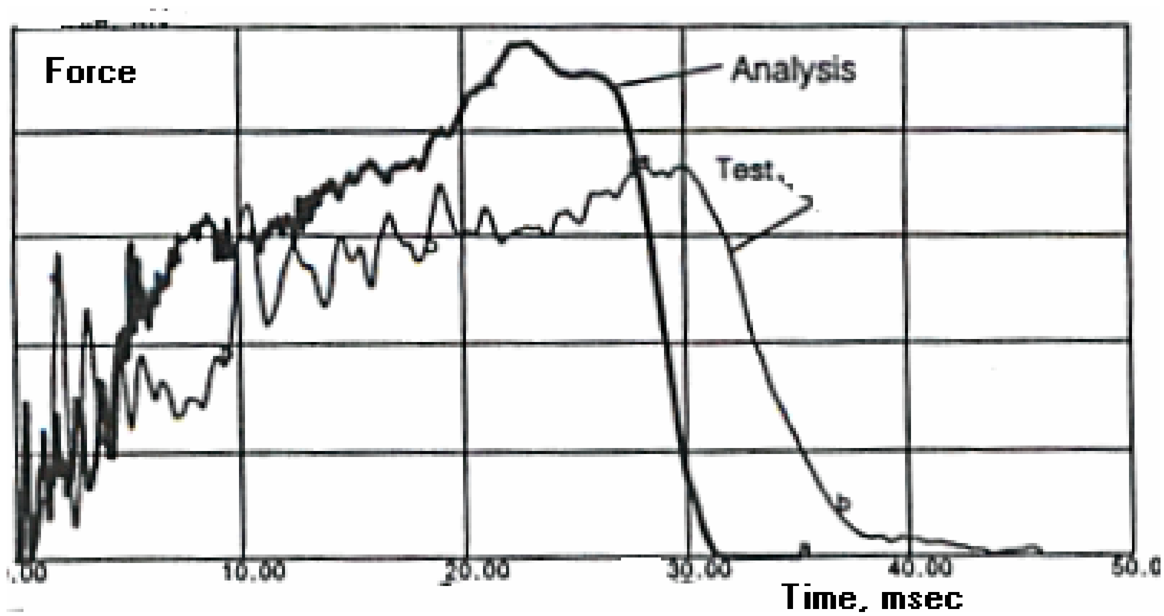

Fig.7. Analysis: Curve from the MDB-to-Skateboard impact test simulation using the Drop Silo test curve from Fig. 6.Test: MDB-to-Skateboard impact test curve.

From Fig. 7 it is clear that when the honeycomb Drop Silo stress-strain curve is used in the simulation, the simulation over estimates the skateboard test results. When the static strain-stress curve is used in the simulation, the analytical results are sufficiently close to the experimental test results, Fig.8. This phenomenon will be addressed next.

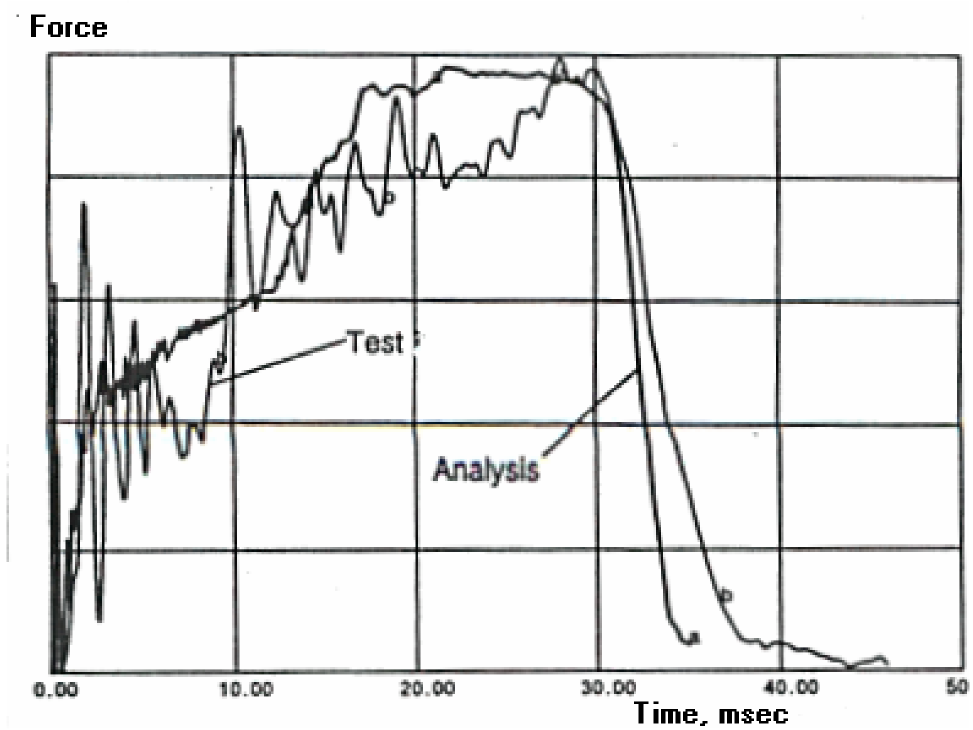

Fig.8. Analysis: Curve from the MDB-to-Skateboard impact test simulation using the staticTest curve from Fig. 6.Test: MDB-to-Skateboard impact test curve.

Honeycomb Performance under Impact Loads

Practically all known references explicitly/implicitly explain the differences between the honeycomb static and dynamic/impact test results by the strain-rate effect. Such explanation contradicts to the fact that aluminum material is not significantly strain-rate sensitive. The test results conducted during the MDB FEM development suggest a possible explanation of the difference. The difference looks like due to the way, how the tests are conducted rather than due to the strain-rate effect on the honeycomb as “material”. The way, how the tests are conducted explain the “size effect” of the honeycomb specimen. The effect of the air in the honeycomb cells and gravity force from the Drop Silo head will be presented here as the difference reason in question.

The Effect of Honeycomb Cell’s Air

The approach used here to assess the effect of honeycomb cell’s air on the honeycomb stresses during Drop Silo tests is similar to that described in [10], but more general expressions are derived here. It is assumed that during the impact test in the T-direction, the honeycomb sample is sufficiently copped from both upper and lower sides by the test machine facings. It is assumed that not much air could escape from the cells during the very short-time impact tests duration.

The sample stress and volume are

$$\sigma = \sigma^{honey} - p^{air} + p_0^{air}\ , \ V = V^{air} + V^{honey}\ , \qquad (6)$$

where: σ^{honey} is the stress in aluminum sheets of honeycomb sample, p^{air} and p_0^{air} are the cells’ current and initial air pressures, V, V^{honey}, V^{air} are the honeycomb sample overall volume, aluminum sheets volume and cells’ air volume.

The honeycomb sample volumetric strain is

$$\varepsilon_v = \frac{V - V_0}{V_0} = \left(1 - v^{honey}\right)\left(v^{air} - 1\right),\ v^{honey} = \frac{V^{honey}}{V_0},\ v^{air} = \frac{V^{air}}{V_0}, \qquad (7)$$

where: V_0 is the honeycomb sample initial volume.

Assuming that cell’s air is the ideal gas, and the original air pressure is equal to 1atm=101,325Pa, we have

$$p^{air} V^{air^{1.405}} = p_0^{air} V_0^{air^{1.405}} = const\tan t\ ,\ p^{air} = 101{,}325\left(\frac{1}{1+\varepsilon_v}\right)^{1{,}405}. \qquad (8)$$

Example. Let $\varepsilon_v = -0.2$, Then $p^{air} = 0.037MPa = 0.037E-03kN/mm^2$.

That example shows that the air pressure is approximately 11% of the average stress from the Drop Silo tests. That increases the Drop Silo test forces by approximately 11%. The increase is subjected mostly to the minimal cells air escape assumption.

In the static compression tests, it is enough time for most of the cell air to escape from the compressing cells. In the Drop Silo impact tests, the cells air does not have enough time to escape. Most of the remaining air is compressed and increases the honeycomb resistance in the tests.

In skateboard tests, the cells air effect is minimal. During the MDB-to-Skateboard tests, the impact direction is not always in the honeycomb T-direction, therefore the cells are rotated slightly, but enough for cells’ end cross sections not to be copped. Therefore, most of the air had escaped from the cells not affecting the skateboard load cell measured force.

The cells air effect looks in part to be a more accurate than strain-rate effect explanation of the difference between the static and impact stresses in the tests.

The Effect of Gravity and Specimen Size in Honeycomb Drop-Silo Test

In Drop Silo test, a vertically oriented load cell is usually used to measure impact force from the falling down on the honeycomb sample Drop Silo head [11]. The Drop Silo head equilibrium equation (neglecting the specimen mass, which is small) is

$$F - Mg = M\,\frac{dv}{dt}, \qquad (9)$$

where: M is the Drop Silo head mass, v is the Drop Silo head velocity, and g is the free fall acceleration.

By multiplying both sides of Eq. 9 by $v = \frac{dz}{dt}$ and v, (z is vertical axis) we have

$$\left(F - Mg\right)\frac{dz}{dt} = Mv\frac{dv}{dt}. \qquad (10)$$

By integrating both sides with respect to time t, taking into account that $t=0$ and $z=0$ when Drop Silo head touches the specimen, v=0 at the end of impact, we have

$$F = Mg + \frac{Mv^2}{2\Delta}, \qquad (11)$$

where: Δ is the specimen deflection at the end of the impact.

The gravitation force Mg in Eq.11 does not depend on the specimen properties. It is present in the Eq.11 and in the load cell measurements because the impact is vertical, and a vertically oriented load cell measures vertical force, which is a sum of gravity and specimen resistance (second member in Eq. 11) forces. In a horizontal impact force Mg would not be present. In the test, the Drop Silo head mass was 305*kg*, then (g=9.81m/sec**2) Mg=2,992*kN*. The average force measured by the load cell was 25kN. Therefore, the real specimen related force was by approximately 12% lesser.

Note that when computing the stresses as force over the specimen cross section area, we would find that the bigger the specimen cross section area the lesser stress would be from the same gravitation force Mg. That might be the reason, why the size of specimen was found in [4] to affect the test stress.

The above analysis shows that the honeycomb cells' air and gravity increase the Drop Silo force and the honeycomb "material" properties by approximately 23%. Based on that results, the decision have been made to use the static rather than the dynamic/impact experimental curves, Fig. 8, in the MDB FEM in spite of the impact environment.

The Effect of the Mat 26 Input Stress-Strain Curve

The curve in Fig. 4 (similar to the presented in [6]) is the commonly used simplification of the curves in Fig. 2, 3, and 6. The simplification is that the Fig. 4 curve does not have stress fluctuation, which is present in test data. That simplification, however, is sufficient when a simulation of honeycomb is used as an energy absorber only, and when an "one-element" FEM is used. The Fig. 4, however, gives a computationally important message that at zero strain the curve must not have a zero or negative value [6,7].

The presence of the fluctuation, and the presence of the first peak of the curve in particular, are important to simulate the localized crushing phenomenon and how the deformed geometry of FEM evolves during the simulation.

During the compression tests, the cell walls deform (crush) locally in the accordion-like manner. The local crash propagates gradually in the direction from one to the other end of the specimen, while the rest of the specimen remains intact. The specimen cross section dimension does not change significantly while the specimen length reduces. In a fully compressed specimen, the cells cross sections remain open.

Fig. 9 shows the evolution of the FEM deformation when the stress-strain curve is without the first peak and fluctuations, as in [4]. All model elements are deforming simultaneously.

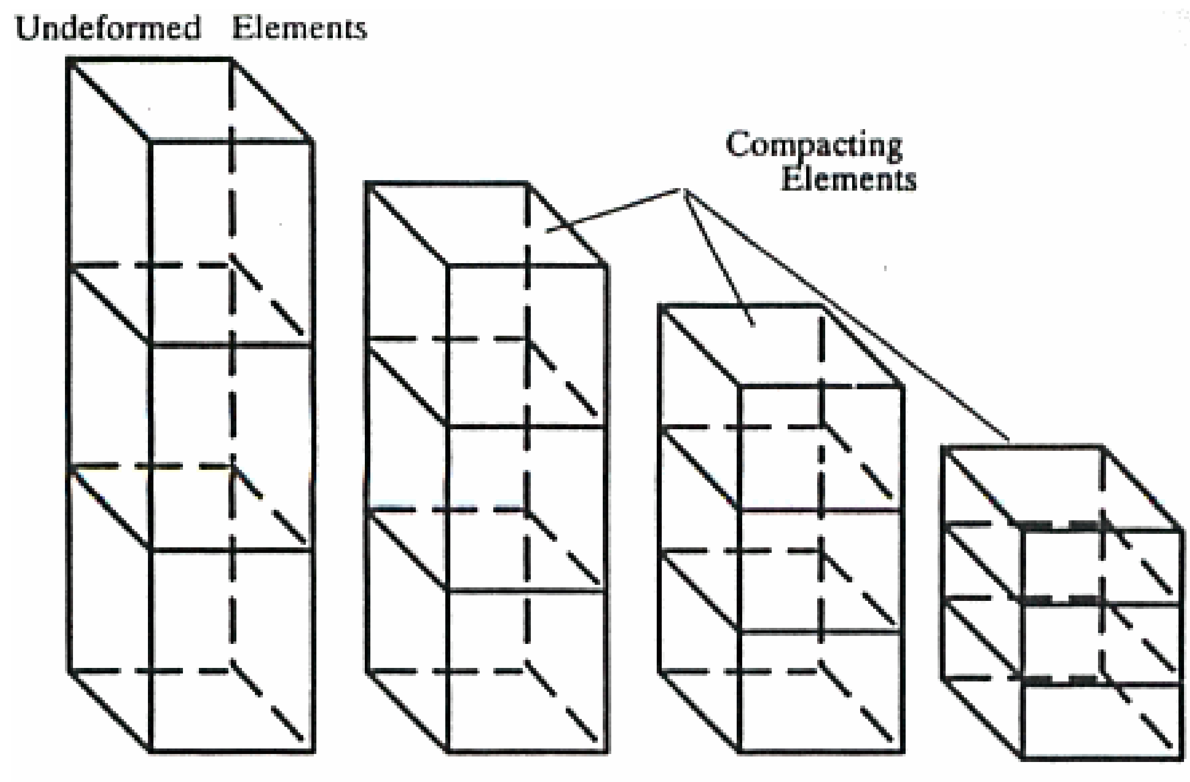

Fig.9. Simultaneous brick element deformation using all positive slopes of stress-strain curve, Fig. 4.

When the curve from Fig. 6 is used, the model deformation localized first, Fig. 10, in the first element. After that element is fully compacted, the second element starts deforming, and so on. Fig. 11 shows how the honeycomb deformation is localized in the MDB FEM.

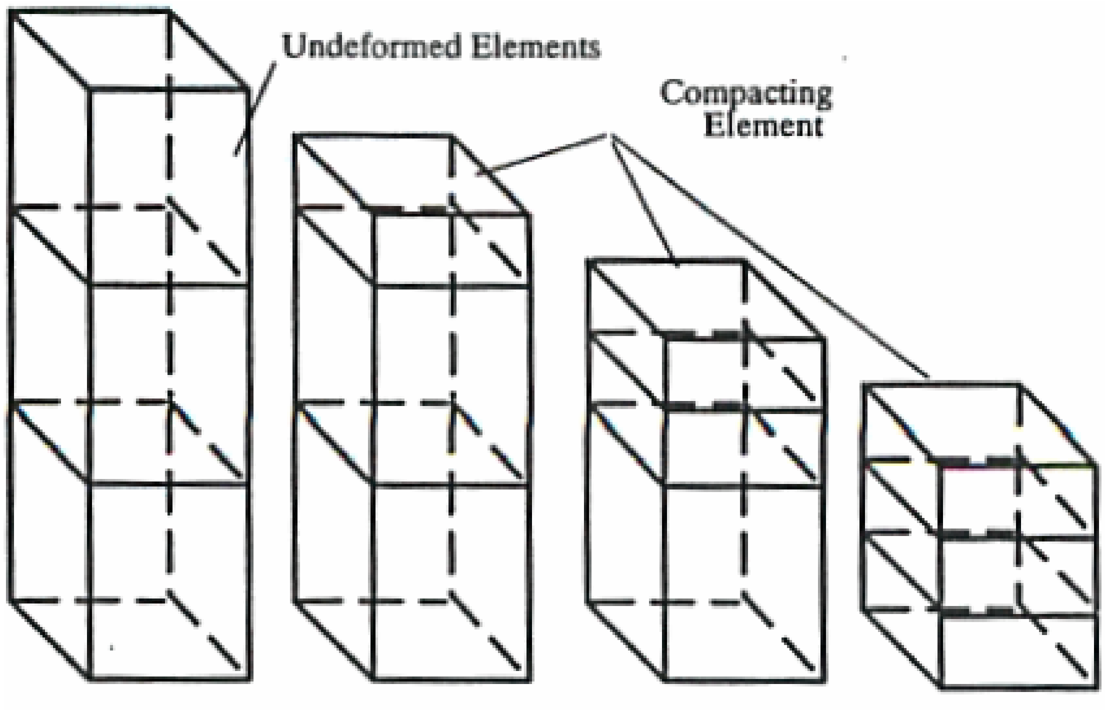

Fig.10. Progressive (localized) brick elements deformation using stress-strain curve with negative slopes, Fig. 6.

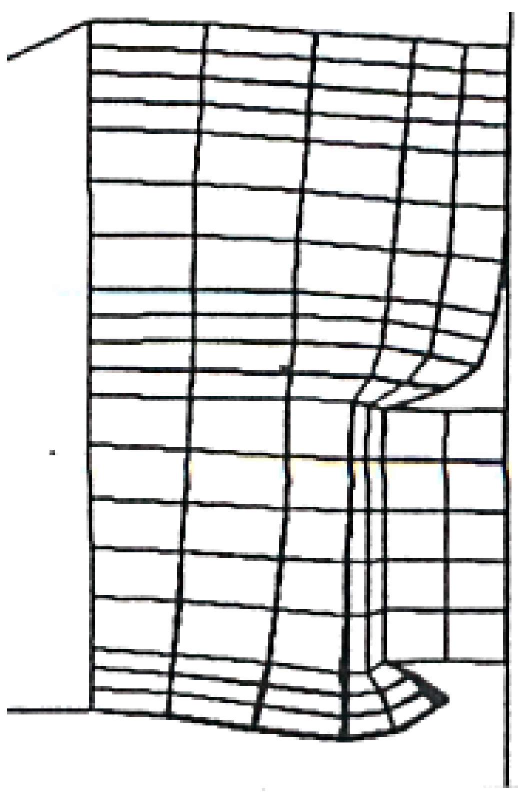

Fig.11. Localized honeycomb brick elements deformation in the MDB.

Conclusions

1. Modeling honeycomb in FEM as a material rather than a cellular structure provides significant (computer time-wise and cost-wise) advantages, but produces side effects, which must be taken into account when conducting "material" tests to make them consistent with a particular application.

2. The difference of the aluminum honeycomb test data under static and dynamic/impact loads does not look to be due to the strain-rate effect, but rather to the:

   a) compression of the air in the cells,
   b) gravity force from the test device drop head.

3. The input from static tests is more sufficient than the input from impact tests in a simulation of honeycomb under impact loads where: honeycomb cells are not capped, and the applied load and honeycomb cell axes are horizontal.

4. The gravity force is independent of the testing specimen. The bigger the specimen cross section area the smaller the stress from the gravity force, and lesser the "size" effect.

5. The bigger the honeycomb-cell cross-section (the lower the honeycomb density) the bigger the amount of air in its specimen. Therefore, the "strain-rate" effect in the low-density honeycomb looks to be higher than in the high-density honeycomb.

Acknowledgment

The successful modeling of honeycomb in the MDB FEM would not be possible without Dr. Hallquist (LSTC) cooperation and help, and without Dr. Steve. M. Rohde and Dr. Phil Oh (GM) help and support particularly in the revision of the mathematics, summarizing and interpretations of the extensive test data, and financing the developments.

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