Application of Inelastic Analysis of ABAQUS in Japanese Industry

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Abstract: In Japan, social demand for heavy industries seems to have been saturated, resulting in the center of the balance of the engineering population deviating toward the field of products with faster delivery times and lower prices. In such a field, while the constraints due to the trend in demand and cost always take precedence over all others, safety and environmental issues are inherently receiving public attention. Accordingly, the analysis of the ultimate state of products, as represented by the crash of automobiles or the dropping of mobile devices, is strongly desired within actual design cycles.

On the other hand, the global trend of replacing conventional metallic parts with resin materials has largely contributed to value-added modern industrial products. However, there are circumstances inherent in the resin materials such that they cover widespread types, and many of them are purchased as parts or components and are cheap. Accordingly, the effort for identifying the constitutive laws of the resin material is likely to be discouraged. That is to say, despite the rapidly growing need for resin conversion, costly modeling of the resin materials hampers the management of FEM.

Based on the above-mentioned circumstances, this paper will cover current trends in Japan for the identification of resin material models and examples of its practical application.

Keywords: Inelastic, Elasto-plastic, Visco-elastic, Buckling.

1. Introduction

These days, various nonlinear structural analysis software with sufficient reliability are on the market and the lower price of hardware and multifunctional pre/post-processors are providing momentum for it. In Japan, with the automobile industry getting into full swing, there are more than a few cases of nonlinear FEM being introduced, even at small-scale parts manufacturers.

Tracing nonlinear behaviors, however, inherently holds difficulties such as an inability to superimpose, path dependency, and the lack of any guarantee for uniqueness and the existence of a solution. Conventional design approaches have been developed by ingeniously avoiding these difficulties, and therefore, introducing nonlinear FEM analysis may not always be appreciated at the actual design site.

On the other hand, it is also true that the assurance of reliability in the nonlinear region is increasingly required. Under high loading, material nonlinearity as well as geometric nonlinearity of thin-shell structures or boundary condition nonlinearity at the interfaces between members is exhibited. In the fields of highly sophisticated products, there are more than few cases where these nonlinear behaviors often put a burden on not only analysis, but testing and prototyping as well.

In the past several years, ABAQUS, the leading edge of the implicit method, has added the explicit method to its line-up, and LS-DYNA is also implementing both the implicit and the explicit methods. Consequently, the ability to solve highly nonlinear problems, especially for two of them, i.e., geometric nonlinearity and boundary condition nonlinearity, has been extensively improved. However, as for material nonlinearity, the issue of defining the constitutive law of materials remains unresolved. This is due to the fact that this issue may not be resolved solely by using FEM capabilities, but rather may be deeply involved with the management of FEM.

Bearing in mind the issues referred to above, this paper will cover the current trend in inelastic analysis in Japan.

2. Changes in industrial structure and nonlinear FEM in Japan

Japan is an island nation positioned at the east end of the Eurasian continent. With this geographic advantage, even though somewhat turbulent at times, Japan has historically experienced the good fortune of remaining the dominant nation in the region for more than 2,000 years. On the other hand, since a large portion of the national land is located on unstable portions of the Earth's crust, the usable area of flat land is very small and much of the nation's energy and mineral resources are not self-sufficient (except for an abundant supply of limestone). As a result, the trends in the nation's industries are never stable, but their rise and fall has been alternatively repeated every 20 years. Over the past 60 years, an upward rise resumed in the order of the textile industry, heavy industry and automobile industry.

The trend in nonlinear FEM has been strongly influenced by changes in the economic climate. The transition of nonlinear FEM applications from 1991 to 2006 is shown in Figure 1 [(1)]. FEM technology plays a part in the history of its growth, i.e., FEM was originally fostered in the fields of sophisticated heavy industries, such as aerospace and nuclear energy. As indicated in Figure 1, 1991 was the time when these sophisticated technologies had matured and the UNIX computers equipped with the graphic capabilities had been brought into the market in earnest. That is to say, this era corresponds to the transition time of the nonlinear FEM from its research stage to popularizing stage. This figure indicates that the foundation of the nonlinear FEM was laid in the key industries as represented by steel making in this era.

However, the social demand for the heavy industries recently seems to have been saturated, and as a result the center of the balance of the engineering population is deviating toward the field of products with faster delivery times and lower prices. In such a field, the worldly constraints due to time and cost, or trends in civilian use always take precedence over all others. Now we enter the next era in which it would become very difficult to support the maintenance of the nonlinear FEM solely by the academic side.

On the other hand, a cluster of these consumer products inherently gains the spotlight for addressing safety and environmental challenges at any time. Presumably to say, though many different opinions may be given, in contrast to that the safety design for the nuclear power plants at a cost of two billion dollars per one station is conducted mainly by the political concern, the assurance of human life for a car at a price of 20,000 dollars is required directly by people's immediate concern. The statistical result in 2006, for example, shown in Figure 1 indicates a sharp increase in demand for the nonlinear FEM for the analysis of the most extreme region as represented by the crashing of automobiles or the dropping of mobile devices.

Under these circumstances, demand for inelastic analysis is now in rapidly increasing. This paper will discuss the current findings beginning with the identification of material models as the most essential matter.

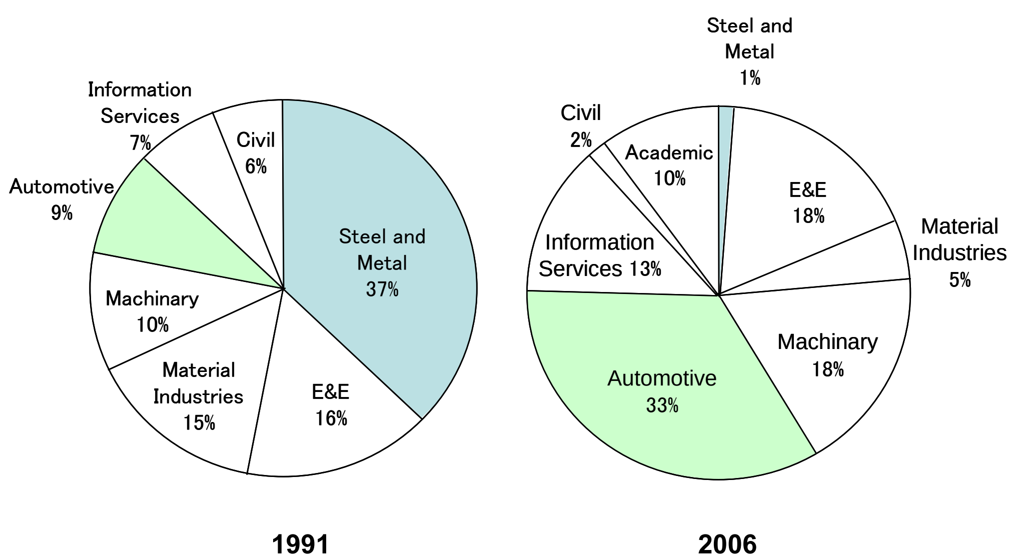

Figure 1 Change in the industrial field applying nonlinear FEM .

(From the investigation by Japan Association for Nonlinear CAE[1])

3. Nonlinear FEM and identification of resin material models

The global trend in replacing conventional metallic parts with resin materials has largely contributed to value-added modern industrial products. This is due to the advantages of resin material, such as easy the relative ease at which it can be shaped as well as various functions it imparts on materials thanks to its plasticity or viscosity effect.

Conversely, not only the composition of the resin material can easily be modified, but also it is not rare to see changes in the properties of resin material due to production conditions and subsequent aging. Accordingly, another aspect may appear such that the effort made for the exact definition of the mechanical properties (apart from chemical request on manufacturing) might not receive a good return. Particularly, the circumstance such that many resin-made parts are purchased as completed products and very inexpensively is likely to promote this tendency. Consequently, the fact that material models cannot be easily identified hampers the management of FEM.

However, even without giving automobile and electronic equipment examples, requests for resin conversion are in rapidly growing. This paper will focus on the identification of resin material models and organize its recent trends.

3.1 Identification of elasto-plastic model of resin material

The most simply used of all mechanical tests of materials is the tensile test. But it is known that there is a limit in the amount of uniformly drawn strains due to occurrence of necking (plastic instability). Considering a condition under the uni-axial tension, the applied load P is expressed as a product of the sectional area A with the resultant stress σ, i.e., P=σA. Its total differential is

$$dP = \sigma dA + A d\sigma \quad \cdot\cdot\cdot (1)$$

Since dσ usually takes a positive value due to the hardening of the material, but dA always becomes negative by tension, we know that dP can always take a negative value. For simplicity, assuming the volume of the material remains unchanged, the increment of logarithmic strain is

$$d\varepsilon = \frac{d\ell}{\ell} = -\frac{dA}{A} \quad \cdot\cdot\cdot (2)$$

By substituting it into the condition of dP=0 (maximal value), the maximum loading condition becomes the following expression.

$$\frac{d\sigma}{d\varepsilon} = \sigma \quad \cdot\cdot\cdot (3)$$

Now, if the stress-strain relation of the material is expressed as $\sigma=C\varepsilon^n$, the load reaches its maximum when ε=n, and subsequently the instability due to softening appears. As presenting the result only, in case of the material following such a power law, necking will occur at the following conditions.

- occurrence of diffusive necking : ε =n
- occurrence of local necking : ε =2n

・・・(4)

For example, general metal materials have a value in the range of n=0.2 to 0.3. After necking occurs (especially local necking), the assumption of the uni-axial stress state in the test specimen is no longer held, and therefore, it can be said that only the strain range within double figures in % at most holds the tensile test being valid.

An ISO tensile test specimen (2) formed from PBT resin (polybutylene terephthalate, Toyobo) and propagation of necking observed in the tensile test are shown in Figure 2. This type of material exhibits the unique phenomenon of neck propagation due to the occurrence of a partial plateau along the path. Spots seen in the photograph of the surface of the specimen are paint sprayed for visualization. As noted in the load-tensile displacement relation, the load sharply drops when displacement exceeds about 20 mm, and subsequently the load is kept nearly constant. This corresponds to the occurrence of necking and its propagation.

The preceding research work (3),(4),(5),(6) reports that the deformation behavior in way of necking was successfully duplicated through performing trial-and-error base analysis aiming to duplicate this type of load-tensile displacement relation. In this study, a 3D model was provided as shown in Figure 3, and an attempt was made to iterate FEM analysis within the feedback loop of the optimizing computation by the generic algorithm (GA). Within the feedback loop, the duplication of the load-deformation relation was attempted along with the iterative modification of the stress-strain relation.

ABAQUS/Standard, as a solver, was applied, and the feedback loop was structured using Python, one of the modern script languages. ABAQUS provides a special feature that enhances the affinity with Python, so it is comparatively easy to construct a system. In the previous investigations, many of them supposedly use the Design of Experiments (DE) as the method of the optimizing computation. However, in order to avoid the difficulty in specifying the initial values, the real type GA using the simplex crossover with good convergence was applied.

A comparison of the results from approximation analysis with the experimental results in terms of the history of load-tensile displacement relation and strain is shown in Figure 4. An estimated stress-strain relation is shown in Figure 5. A comparison of the strain distributions over the bottle necked portion is shown in Figure 6. The elapsed time taken in the trial of the optimization was about three hours using a PC. Although the analysis this time was limited to only isotropic material models, it aimed to simply obtain the stress-strain relation in the tensile test involved with necking, and consequently the intended purpose was accomplished.

The measured values of the strain shown in Figure 6(a) are made visible using the digital image correlation method (DIC). In this method, a CCD camera tracks over the whole field of view along the surface of the test specimen that was marked with spray in advance. By digitizing the captured image data, the components of strain at every instance can be obtained.

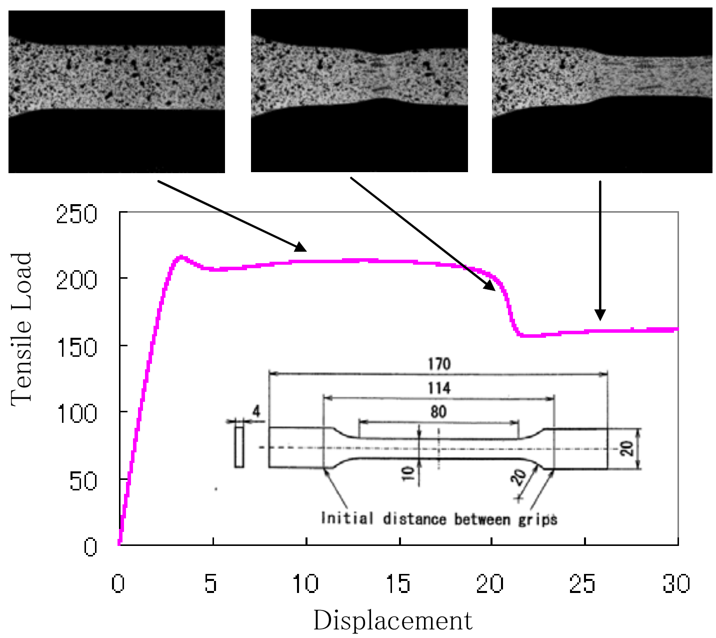

Figure 2 Necking in ISO tensile test specimen of PBT.

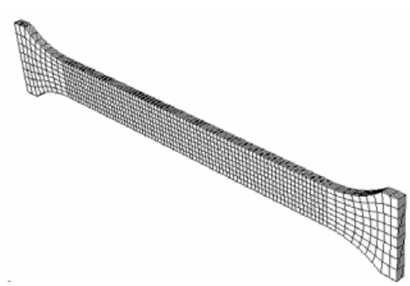

Figure 3 FEM model of ISO tensile test specimen.

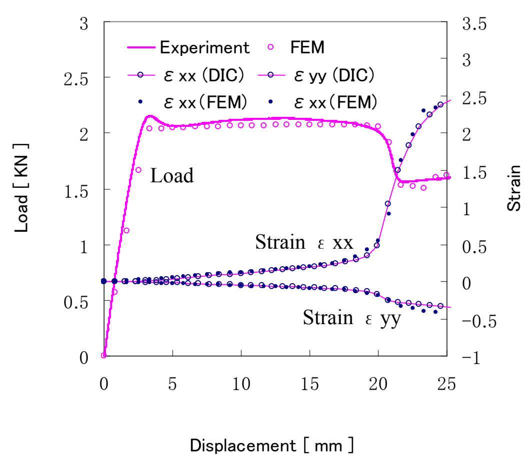

Figure 4 Load and strain response of tensile test specimen with neck propagation.

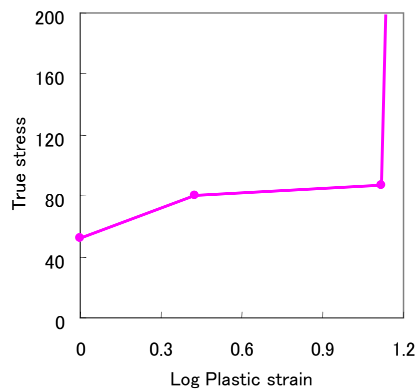

Figure 5 Estimated stress-strain relation.

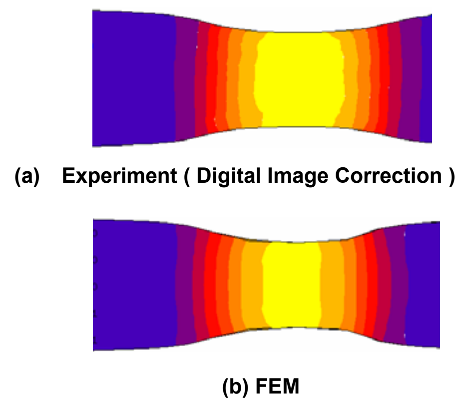

Figure 6 Comparison of Strain result.

3.2 Identification of visco-elastic model of resin material

Resin materials like plastic or rubber inherently have a property known as stress relaxation or creep. Even if the material seems hard at first glance, under high temperature or after a long time elapses, it exhibits rheological behavior and relaxation for internally induced tension is attempted. The visco-elastic model exhibits such behavior of relaxation (stress relaxation) by making its modulus of elasticity decayed with time.

When the model in the form of stress relaxation is kept constant by giving instantaneous strain and the stress response after t is considered, its ratio is called the stress relaxation function. Usually, for the model in the form of stress relaxation, the generalized Maxwell model with multiple Maxwell models in a parallel series as shown in Figure 7 is used. As illustrated in Figure 8, each Maxwell model in the series is relaxed in sequence. The spring element located at the left end of the model represents the residual elasticity left after the relaxation was completely finished. The response at this time is described as follows.

$$E(t) = E_e + \sum_{i=1}^{n} E_i e^{-t/\tau_{M_i}} \quad \cdots (5)$$

In general purpose FEM, the modulus of elasticity E_i and the relaxation time τ_i and E_e of each element composing the generalized Maxwell model are given as the input data. For actual visco-elastic materials, at most more than 20 Maxwell models are generally used. It is known that, provided with the sequence of τ_i in a manner such as the next one has an order of time greater by one digit than the former, the response over the full range can be expressed by a curve with appropriate smoothness. Not only ABAQUS, but also many of other general purpose FEM provide a specific feature for identifying the material model from Eq.(5). But if this feature is actually used, there are some difficulties in the convergence in the optimizing computation in many cases and therefore it is not so easy to obtain satisfactory results.

In addition, the measurement of visco-elastic materials is generally performed within the frequency domains, which is a contributing factor to the difficulty in applying practical FEM. That is because the relaxation curves derived from the frequency domain have to be converted into the time domain base. For the response from the generalized Maxwell model when strains of sinusoidal waveform are given as the input data, only the result is shown below.

$$E'(\omega) = E_e + \sum Ei \frac{\omega^2 \tau_i^{\,2}}{1+\omega^2 \tau_i^{\,2}} \qquad E''(\omega) = \sum E_i \frac{\omega \tau_i}{1+\omega^2 \tau_i^{\,2}} \qquad \cdots \quad (6)$$

For epoxy resin material, as a subject of interest, the result from the actual measurement of E'(ω) and E''(ω) are plotted as shown in Figure 9. The region showing a high modulus of elasticity in the high frequency domain is called the glassy region, followed by the region showing low modules of elasticity in the low frequency domain as the rubbery region, and the intermediate region between the former two as the transient region. In this example, the modulus of elasticity is found to vary over the range of frequency in 12 digits.

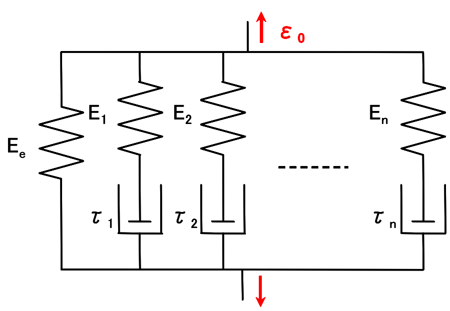

Figure 7 Generalized Maxwell model.

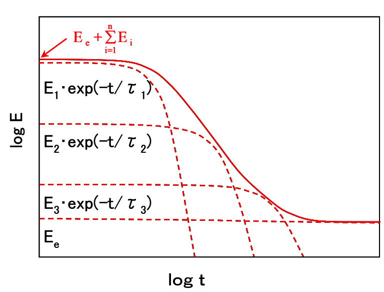

Figure 8 Relaxation of generalized Maxwell model.

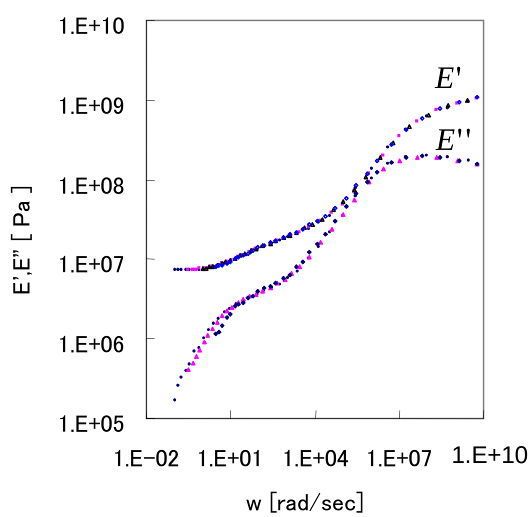

Figure 9 E'(ω) and E''(ω) of epoxy resin material.

The modulus of elasticity E_i, relaxation time τ_i and E_e of each element composing the generalized Maxwell model can be obtained directly from these E'(ω) and E"(ω) using Eq.(6). An example of a specific program using Excel is shown in Figure 10. As this program incorporates the following supplemental features, it allows the identification of the real visco-elastic material models.

- Leveling of relaxation spectra
- Fix defective data (due to incorrect temperature control in the experimental measurement)
- To make the modulus of elasticity of the Maxwell model positive definite

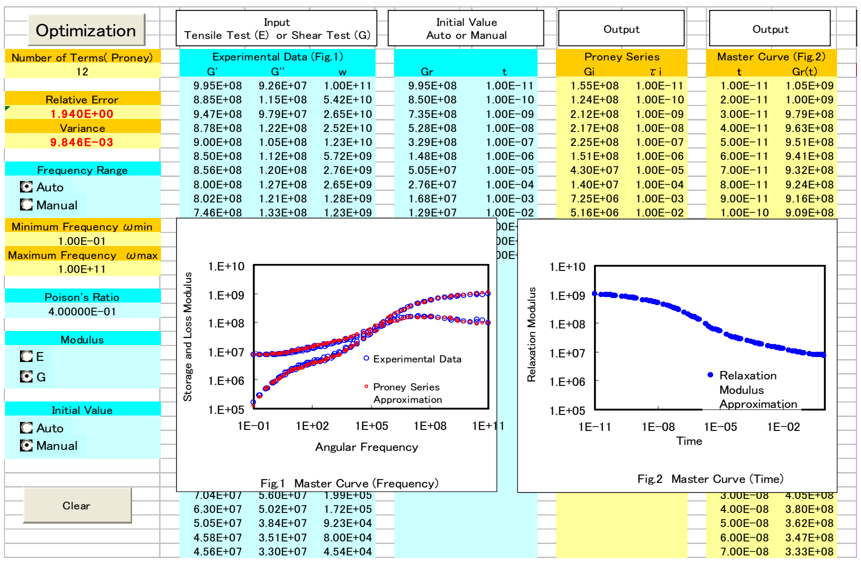

Figure 10 Visco-elastic curve fit program using Excel.

4. Inelastic analysis in large deformation region

4.1 Compressive buckling of box member for car bodies

Development of mutual complementing between ABAQUS/Standard (Implicit method) and ABAQUS/Explicit (Explicit method) recently appears to be progressing rapidly. As an example of its application, a case of compressive buckling of a box member for car bodies is shown in Figure 11. In this type of buckling, buckling is developed in the manner as the web member being folded in succession. Since the level of loading is held during buckling is in progress, this box member can be utilized as a cushioning member of simple structure.

Due to the existence of analytical issues such as large deformation, large strain, plastic buckling and self-contact, there have traditionally been many analysis cases predicting the use of the explicit method. However, from the viewpoint of actual design, there are profound requests desiring the analysis of such problems using the implicit method. That is because of the need for combining complex loading conditions with each other, such as statically mechanical load with thermal loads.

In ABAQUS/Standard, apart from the arc-length method as a conventionally known solution, the artificial damping method is implemented so that the user is now provided with another technique to stably analyze the behavior in the large deformation region including buckling. The load-displacement curve shown in Figure 12 was obtained as a result of the above-mentioned studies. It is a result presenting the characteristics in the experimental result very well. This result was obtained by careful attention paid to the material property (aluminum elasto-plasticity) and the boundary condition at the member ends.

Although ABAQUS/Explicit enables the analysis of the region to the extent of the region covering more developed large deformation, worthy of special note is the very good agreement with the results from ABAQUS/Standard. This is estimated as the result from outstanding performance of the ABAQUS element libraly. This consistency gives the user important assurance in the actual design analysis. The result presented here refers to the result from investigations by the Society of Automotive Engineers of Japan 2006.

Aluminum Extrusion 200 x 75 x 50 x 4t

E=66500Mpa ν =0.3, Sy=212Mpa

Friction Coefficient : 0.4

(Experiment: Courtesy of Mitsubishi Aluminum Co., Ltd.)

Figure 11 Compressive buckling of a box member for car bodies.

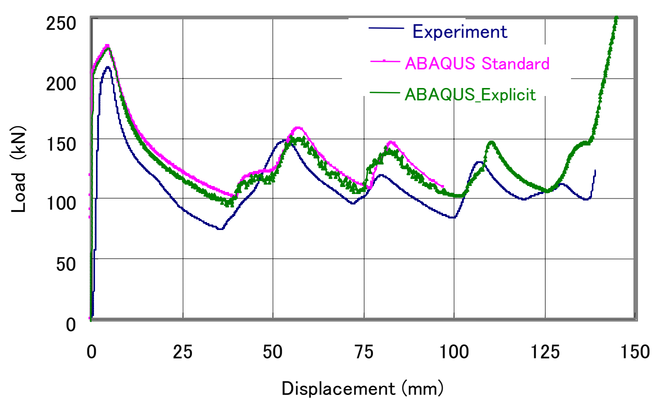

Figure 12 Comparison between experimental data for Load-displacement relation and predictions from implicit and explicit FEM of a box member for car bodies.

4.2 Clothing fitness analysis [7],[8]

Moderate contact pressure by clothing on the human body improves the exercise faculty and corrects body shape, and it is also closely linked to the degree of comfort of clothing. It is usually measured using pressure sensors over a clothed body, but it seems to be difficult to measure accurately due to deformation of the body shape as well as the sensors. In addition, since measurable body parts are limited, it is not so easy to grasp the distribution of the contact pressures.

In this study, the fitting of clothing was analyzed using ABAQUS/Standard. A dummy the size of an average Japanese woman in her twenties was measured in 3-D, and all the measured data were embodied into the dummy that was defined as a rigid body. Since it is difficult to apply any macroscopic constitutive laws to clothing materials, an rubber shell element was combined with rebars. For identifying this material model, both of the uni-axial and bi-axial tensile tests were used, and deformed state of the typical knit fabric samples is illustrated in Figure 14.

Clothing is a problem in which plural stable solutions inherently exist depending on fitting conditions. Starting with the original state of the patterns, the artificial damping method was applied in order to overcome any instability due to wrinkling that occurred during static analysis in progress. An example of the analysis is shown in Figure 15. The contact pressures obtained from the analysis are confirmed to be in good agreement quantitatively with the experimental results.

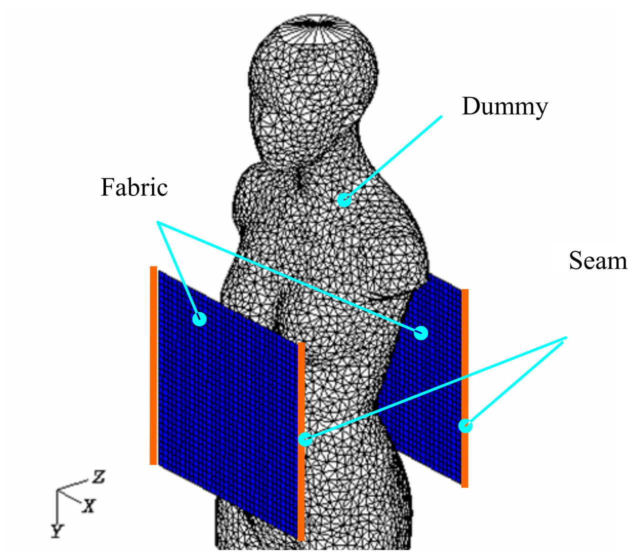

Figure 13 Fitting of clothing on a human body.

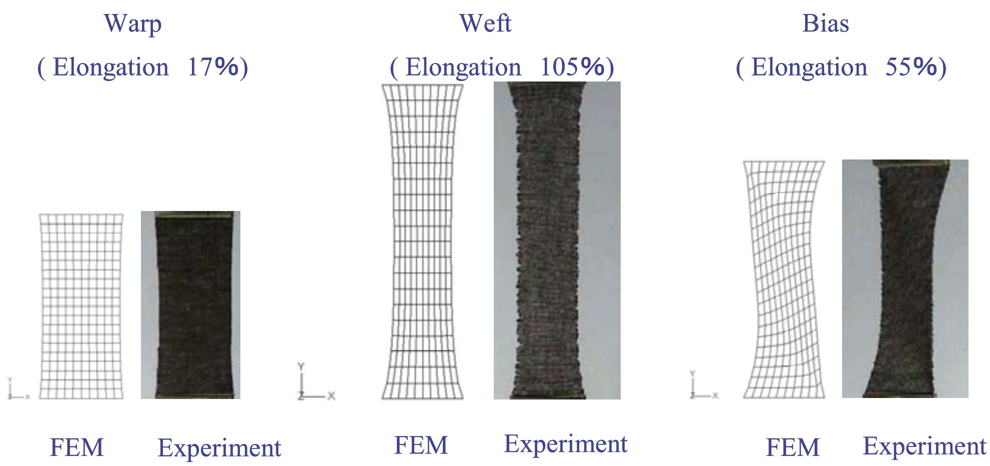

Figure 14 Modeling of knit fabric using rubber shell element with rebars.

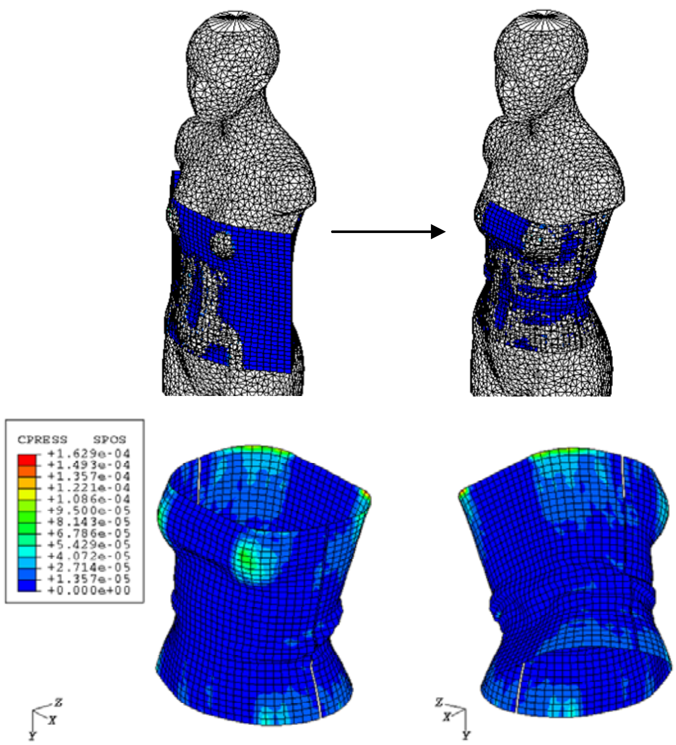

Figure 15 Analysis result for contact pressure.

4.3 Prediction of Equilibrium and Stability of Molten Solder Geometries (9)

Improving the reliability on solder joints is one of the major tasks to achieve downsizing of electronics products. Taking the molten solder profile as an object of study, a new procedure to model solder liquid with a structural FEM has been developed, which enables us to solve an issue of predefining the geometrical profile of solder liquid drops in a state of static equilibrium taking the surface tension into account, and also a problem concerning dynamic stability of the liquid drops.

Molten solder liquid is treated as viscous fluid. Deformation of the material due to its viscosity can be represented by the structural analysis using rheological approach. Two types of the constitutive laws, creep model or viscoelasticity model, can be applied. Such a simple case as the Newtonian fluid, either constitutive law may be employed. Using these types of the constitutive laws in the analysis with time incremental steps, it becomes possible not only to obtain the stabilized shape of liquid drops, but also to analyze problems involved with transient (including dynamic effect) stability.

As the size of a liquid drop is microscopic in a range of 100 to 1000 µm, the effect of the surface tension must become so predominant in the loading conditions. In most of the conventional theoretical researches, it is found that the surface tension is treated as the pressure difference varying according to the surface curvature. However, this method is not only so complicated, but also may lead to numerical instability particularly in the transient analysis subjected to large deformations. In this study, an effective method has been developed in which the surface tension can be represented with good accuracy through simplified input data with allocating the shell element generating a constant membrane force over the surface of a liquid drop

Using our method of three dimensional analysis, an analysis was made for the response of molten solder subjected to enforced displacement given in the shear direction. In the reflow soldering process, even if a chip has been set, in the initial stage, with a little error, as solder melts the chip would move to the exact position on the pattern of the printed circuit board by surface tension force of the solder. This effect is called self-alignment. Due to its passive positioning capability, the self-alignment effect is finding increasing application in optoelectronic packaging where the alignment between the mating components is a critical assembly issue. It provides a cost-effective precision technique(12).

For studies of the response of a molten solder bump under loading in the shear direction, reference can be made to the classic investigation by Goldmann (10). Other than that, there are some theoretical studies(11),(12). In this study we tried to compare with the measurement value by Goldmann. Figure 16 shows the FEM model. The analysis conditions are as follows.

Surface tension of solder : γ = 0.386 N/m	Volume of bump : V = 1.48E-3 mm^3
Radius of the upper pad : r_0 = 0.0648 mm	Radius of the lower pad: r_1 = 0.0914 mm
Downward vertical load : F_A = 3.72E-7 N	(Viscosity of solder: = 2E-3 Pa . sec)

Figure 17 shows the resultant displacements vs. the applied shear force on the upper pad of the FEM model as illustrated in Figure16. By integrating this profile curve, the potential energy of a liquid drop, i.e., the sum of the surface energy and the gravity energy can be obtained. The change in the potential energy derived in this way is plotted in Figure 18. In this figure, the curve with a solid line indicates the results from this study, and Goldmann's experimental data are also plotted. Both of the data show fairly good agreement.

Alternatively, this surface energy may be obtained from the product of the surface area and the surface tension on a liquid drop. In this example, the change in the gravity force may be ignored, and the potential energy may reach very close to the surface energy. Goldmann obtained this potential energy based on the surface area calculated assuming the shape of a sheared molten solder bump represented by an elliptical segment. The curve with a broken line in Figure 18 indicates this numerical solution. Goldmann, however, augured that numerical solutions must become higher than experimental measurements along with increasing deformations, because of approximating a liquid drop with an elliptical segment being not fully sufficient. The analysis performed here to supports this proposition.

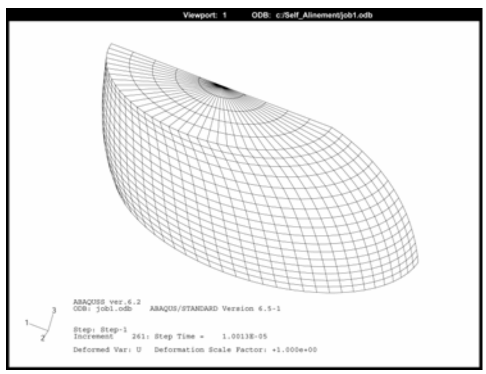

Figure 16 Shearing of molten solder joint.

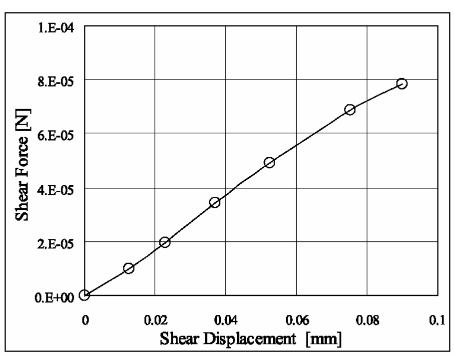

Figure 17 Relationship between shear displacement and force.

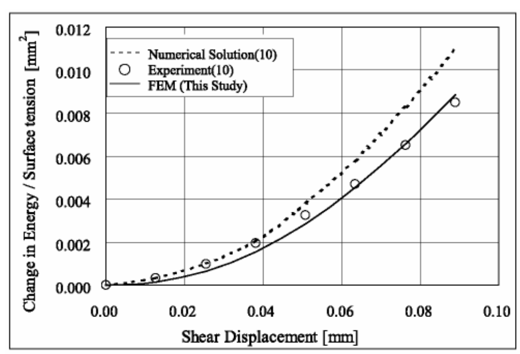

Figure 18 Change in energy of sheared molten solder joint.

5. Conclusion

The identification and its application examples for the material models applied to ABAQUS were presented in this paper. Based on these findings, for the material models with elasto-plasticity, hyper elasticity or (linear)visco-elasticity, it becomes possible to perform analysis, except in extremely unusual ones, as being enough to practical use. Further development along with the availability of these types of analysis is highly expected.

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