2004-01-1659

First Order Analysis for Automotive Body Structure Design –Part 2 : Joint Analysis Considering Nonlinear Behavior

Yasuaki Tsurumi, Hidekazu Nishigaki, Toshiaki Nakagawa, Tatsuyuki Amago, Katsuya Furusu
Toyota Central R&D Labs.,Inc.

Noboru Kikuchi
The department of Mechanical Engineering at the University of Michigan

ABSTRACT

We have developed new CAE tools in the concept design process based on First Order Analysis (FOA). Joints are often modeled by rotational spring elements. However, it is very difficult to obtain good accuracy. We think that one of the reasons is the influence of the nonlinear behavior due to local elastic buckling. Automotive body structures have the possibility of causing local buckling since they are constructed by thin walled cross sections. In this paper we focus on this behavior. First of all, we present the concept of joint analysis in FOA, using global-local analysis. After that, we research nonlinear behavior in order to construct an accurate joint reduced model. (1) The influence of local buckling is shown using uniform beams. (2) Stiffness decrease of joints due to a local buckling is shown. (3) The way of treating joint modeling considering nonlinear behavior is proposed.

INTRODUCTION

We have developed new CAE tools based on First Order Analysis (FOA) since 1999(Nishiwaki[1]). FOA tools are used on the concept design development process. The basic ideas of FOA are:

1) Graphic user interface for automotive design engineers using Microsoft Excel.

2) Use of sophisticated formulation based on the theory of mechanics of materials.

3) A topology optimization method using functions oriented elements such as beam elements.

Using the above ideas, design engineers can easily utilize FOA tools and determine basic layouts based on structural mechanics without spending much time. Therefore FOA tools have come to be very significant in the concept design process.

On the other hand, as FOA has used more widely and deeply, advanced functions to solve various problems are required. Especially a problem with respect to joints is one of the most significant one for automotive body structures. For example a global torsion stiffness of a body-in-white greatly depend on joint flexibilities. Therefore their behavior about joints must be accurately estimated in the analysis. Generally shell elements are used in order to construct finite element models. In the concept design phase, where FOA tools are used, these shell element models of joints are replaced with rotational spring element models (EI-sayed,M.E.M[2]) whereas rails, pillars and frames are modeled with beam elements to simplify the analysis. However, it is very difficult to obtain the good accuracy using these spring elements. It is considered that there are two reasons. One is the transformation error from shell element models to spring element models (Kim[3]). The other is a bad effect of nonlinear behavior due to local elastic buckling. Various studies about the former one are addressed and a few different models are used (Kim[4],Lee[5]). However no studies about the latter one have ever been heard, as far as I know. Automotive body structures have the possibility of casing local elastic buckling since they are constructed by thin walled cross sections. Once local elastic buckling occurs, stiffness decreases and the yield point becomes lower. Therefore it is very important to consider this buckling. This behavior cannot also be evaluated even if joint models are constructed using detailed linear shell elements.

First of all, in this work we present the concept of joint analysis in FOA. We propose to use Global-Local Analysis to obtain both a good accuracy and an adequate speed for analyzing. For realizing this concept, several unknown problems must be resolved such as how to construct a good reduction model for static and dynamic behavior, etc.

As a first step to resolve some unknown problems, we focus on the nonlinear behavior due to local elastic buckling in order to see if we should use a nonlinear model. Our approach is:

(1) The influence of local buckling is shown using uniform beams. Nonlinear behavior is predicted using a beam elements, whose cross section properties are calculated based on the theory of effective width (Marin and Diewald[6]).

(2) Stiffness decrease of joints due to local elastic buckling are shown with respect to in-plane and out-plane bending. It is hard to predict nonlinear behavior without using nonlinear analysis.

(3) The two ways of treating how to construct a joint model considering nonlinear behavior is proposed. One is to move a buckling frequency from the present point to the upper point, as much as possible. The other is to use the nonlinear spring constant in the global analysis.

THE CONCEPT OF JOINT ANALYSIS IN FOA

We use Global- Local analysis in order to obtain both a good accuracy and an adequate speed for analyzing in FOA. This way is shown as followings:

(1) Joint configurations are exactly modeled using shell elements for local analysis. Using this model, necessary performance such as stiffness, vibration and strength is estimated. Nonlinear analysis in addition to linear one is performed (Figure 1(b)).

(2) A reduced model based on the above results is constructed for global analysis (Figure 1(b)).

(3) Databases about typical joint configurations are constructed repeating these procedures from (1) through (2) (Figure 1(c)).

(4) The reduced models of the joints are inserted in a global model and global performance is estimated. This analysis is simple and fast. The joint flexibility of the reduced model is optimized for satisfying a target performance (Figure 1(d),(e)).

(5) In the local analysis, the joint configuration (layout) is optimized based on the optimized reduced joint flexibility. In this optimization process, the database is referred and the optimal layout will be found out (Figure 1(f)).

This way is very significant in FOA. But we have to recognize right behavior of joints in order to construct a good reduced model. As a first step we focus on the nonlinear behavior due to local elastic buckling.

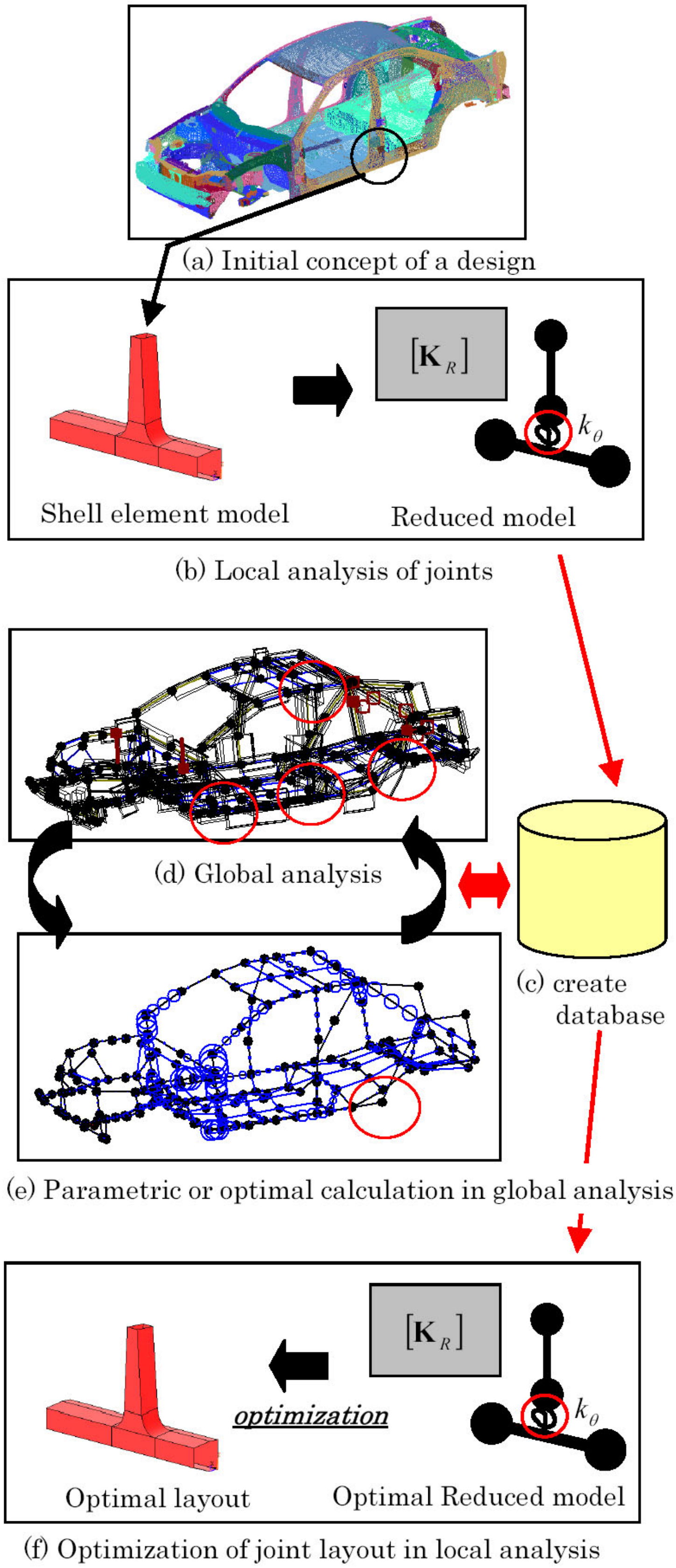


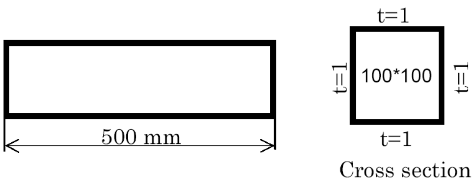
Figure.1 The concept of global-local analysis

INFLUENCE OF LOCAL ELASTIC BUCKLING IN THE CASE OF UNIFORM BEAMS

Before analyzing joints, basic research of local elastic buckling is performed using uniform beam structures. In automotive body structures, individual elements of frame structural members are usually thin and the width-to-thickness ratios are usually large. Then thin elements may buckle locally at a stress level lower than the yield point of steel when they are subjected to compression in flexural bending, axial compression, shear, or bearing (Yu[7]). Stiffness decrease is verified using nonlinear simulation. Moreover this behavior is predicted based on the theory of effective width.

ESTIMATION USING SHELL ELEMENT MODELS

In this section, buckling behavior is calculated using shell element models. We use ANSYS ([8]) for this analysis. Nonlinear analysis is performed including initial deflection that is obtained by 1-th buckling eigenvalue analysis. As shown Figure 2, the uniform box beam element is used with respect to two types of boundary condition, (1) axial compression condition, (2) vertical force condition.



$$E(\text{young modulus}) = 203000\left(N/mm^2\right)$$
$$\upsilon(\text{poisson ratio}) \quad = 0.3$$
$$\sigma_y(\text{yield stress}) = 269\left(Mpa\right)$$

Figure.2 Test model of the uniform box beam

<u>Axial compression condition</u>

Fig.3 shows the deformation at the local elastic buckling load. As shown Fig.4, the local elastic buckling occurred at the lower point (F=3.16e4[N]) than the yield point (F=4.52e4[N]). Stiffness decrease in the elastic domain is confirmed after causing the local elastic buckling. In this case, the axial stiffness became about half of the initial one. This is the significant problem. If this axial stiffness is estimated without considering the influence of the local buckling, the weaker structure than you thought is designed.

<u>Vertical force condition</u>

Figure 5 shows deformation at the local elastic buckling load. As shown Fig.6, the local elastic buckling occurred at the lower point (F=3.82e3[N]) than the yield point (F=4.49e3[N]). Stiffness decrease in the elastic domain is confirmed after causing the local elastic buckling. The bending stiffness did not change so much. In this case the influence of buckling is small.

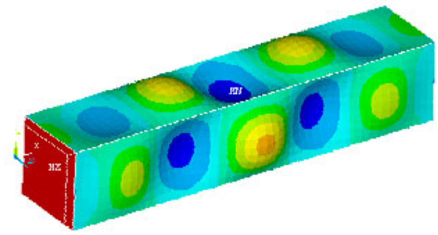


Figure.3 Deformation at the axial load (F=3.16e4[N])

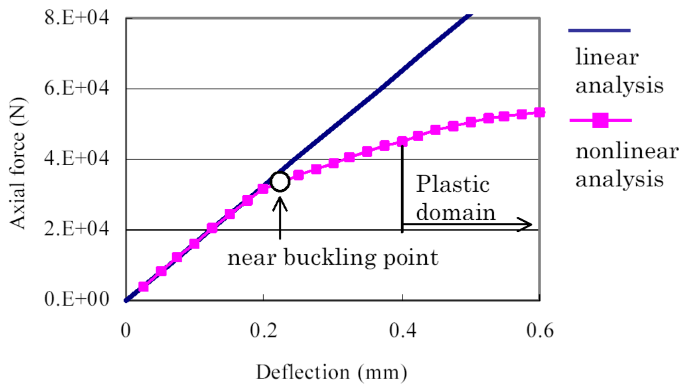


Figure.4 Influence of local elastic buckling under the axial compression condition

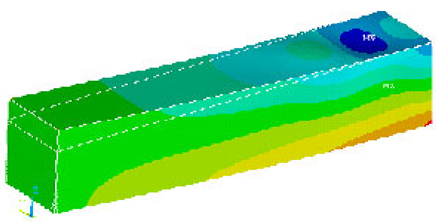


Figure.5 Deformation at the vertical force (F=3.82e3[N])

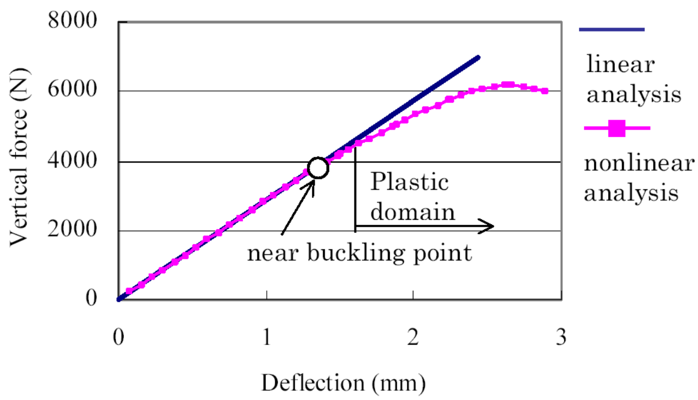


Figure.6 Influence of local elastic buckling under the vertical force condition

This is because only one surface near the rigid point is buckled. However this uniform beam with the buckling trends to reduce the strength compared with the structure, whose local elastic buckling eigenvalue is bigger than the yield point. Therefore this behavior is also the significant problem.

HOW TO TREAT LOCAL BUCKLING IN FOA

In beam structures, the influence of local elastic buckling can be estimated based on the theory of effective width. In this section, effective width under the axial compression condition is calculated and the reduction in stiffness is predicted.

The theory of effective width

The above beam model has uniformly compressed stiffened elements. The effective width (=b) of these elements is determined (Marin and Diewald[6]) as followings:

$$b = w \quad \text{when} \quad \lambda \le 0.673$$
$$b = \rho w \quad \text{when} \quad \lambda > 0.673 \qquad \text{---------------------------} \quad (1)$$
where $w =$ width of the element

$$\rho = \frac{1 - \frac{0.22}{\lambda}}{\lambda} \qquad \text{----------------} \quad (2)$$
where λ is a slender factor determined by

$$\lambda = 1.052\left(\frac{w}{t}\right)\frac{\sqrt{\frac{f}{E}}}{\sqrt{k}}$$
where $f =$ stress in the element
$E =$ Young's modulus of the element --------------- (3)
$k =$ plate buckling cofficient
$t =$ thickness of the element

(1) Compute the normal stress distribution based on a given stress level assuming all the segments are fully effective.

(2) Based on the computed stress distribution and the segment type, calculate effective widths of each segment (referred to Eqn (1)-(3)).

(3) Calculate the cross section properties of the section based on the effective portion of each segment.

(4) The above procedures are repeated until the cross section properties converge.

Then if the next convergence condition is assumed,

$$b_n \to b \quad if \quad n \to \infty$$
$$\text{where} \quad b_n = \text{effective width at } n-th \text{ cycle} \qquad \text{---------} \ (4)$$

we can obtain the effective width using Eqn (5) without repeating (1)-(4).

$$b = \left(\frac{1}{\frac{B}{w} + \frac{0.22}{B}}\right) \qquad \text{---------------------------------}(5)$$
$$B = 1.052\left(\frac{w}{t}\right)\sqrt{\frac{F}{4Ekt}}$$

In the case of the axial compression condition, the total effective width is calculated as shown Figure 7. The influence of local elastic buckling is seen from the point, which doesn't reach the local buckling force.

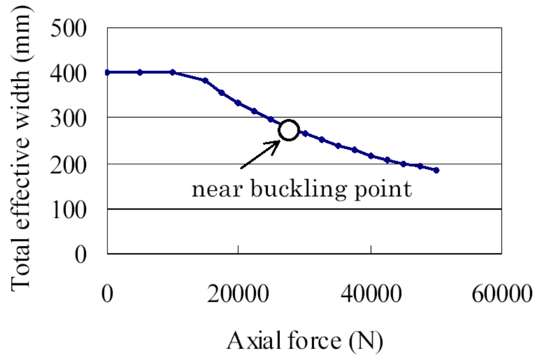


Figure.7 Effective width under the axial compression

The prediction of the influence to stiffness

The axial stiffness is calculated using the cross section properties of the section based on the effective portion. However not all sections have the effective width. As Figure 8 is shown, the portion with the effective width and the rest with the fully effective width exist. Then we use Eqn (6) in order to calculate the axial stiffness. Figure 9 shows the results of three different methods. As a result, the result based on the theory of effective width is well consistent with the result of nonlinear analysis by ANSYS. That is to say, we can predict the influence of local elastic buckling without complicated nonlinear analysis. In the case of the vertical force condition, we can also predict using the same method.

The behavior of local elastic buckling has the possibility of giving thin walled beam structures a big damage with respect to stiffness and strength. Design engineers have to consider these problems in the concept design process. However they don't perform complicated simulation using Finite Element (FE) commercial software. Therefore the above method is greatly effective. It enables the estimation of nonlinear behavior without complicated analysis. Moreover this nonlinear behavior cannot be obtained by linear analysis even if detailed shell element models are used.

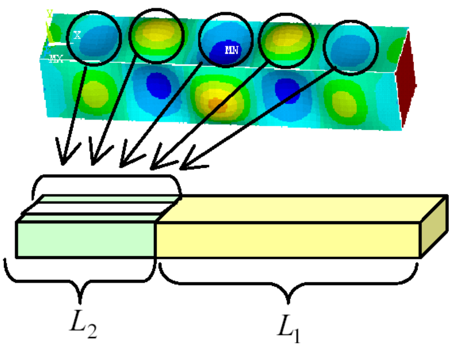


Figure.8 The estimation of stiffness by buckling

$$K = \frac{F}{u} = \frac{EA_1A_2}{L_1A_2 + L_2A_1}$$

$$L_2 = nb$$

where

- K = axial stiffness
- F = axial compression force
- u = axial deflection
- A_1 = cross section area at the fully effctive width
- A_2 = cross section area at the effctive width
- L_1 = length at the fully effctive width
- L_2 = length at the effctive width
- b = effctive width
- n = number of mode

------------------------------------ (6)

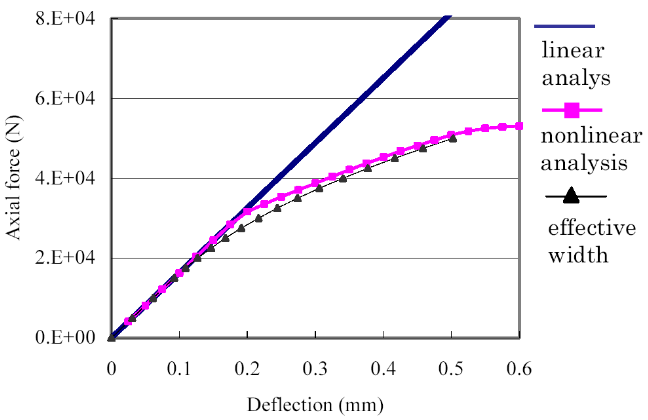
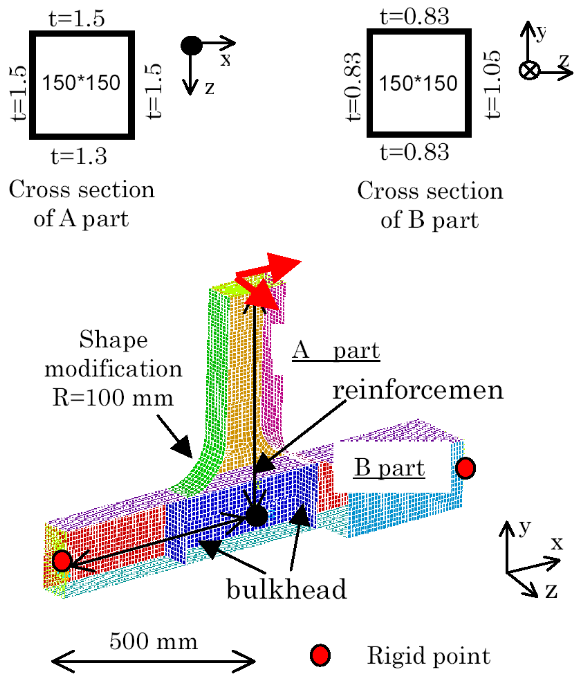


Figure 9 the comparison among three methods

INFLUENCE OF LOCAL ELASTIC BUCKLING IN THE CASE OF JOINT STRUCTURES

In this section, the influence of local elastic buckling with respect to joint structures is studied. The influence with respect to uniform beams is estimated by the method based on the theory of effective width. However, it is unknown if this method can be applied to joint structures. Then we work on the analysis of basic joint structures (Figure 10). The two type of conditions, (1) in-plane bending (2) out of plane bending, and three typical modifications for increasing stiffness, (a) bulkhead (b) reinforcement (c) shape modification in addition to an initial shape are considered. Nonlinear analysis is performed including initial deflection that is obtained by buckling eigenvalue analysis.



$$E(\text{young modulus}) = 203000\left(N/mm^2\right)$$

$$\upsilon(\text{poisson ratio}) \quad = 0.3$$

$$\sigma_y(\text{yield stress}) = 400(Mpa)$$

Figure 10 Test model

IN-PLANE BENDING

Figure 11 shows the deformation of the initial shape at the local elastic buckling load. As shown Figure 12, this deformation by the local elastic buckling occurred at the lower point (F=4.55e3[N]) than the yield point (F=6.07e3[N]) mainly in the joint. Stiffness decrease in the elastic domain is confirmed after causing the local elastic buckling. In this case, the bending stiffness became about half of the initial one. This behavior cannot be predicted using the theory of effective width because this buckling is not a general plate one.

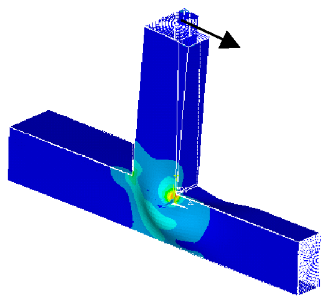


Figure.11 Deformation at the vertical force (F=4.55e3[N])

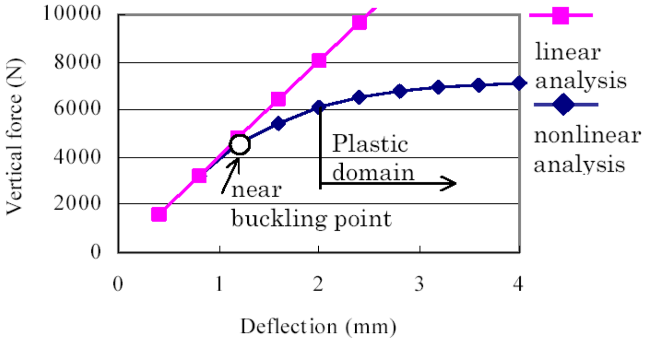


Figure.12 the Influence of the local elastic buckling under the initial condition

Table 1 shows the rate of stiffness decrease. In all of cases, the deformations by the local elastic buckling occur at the lower point than the yield point (Figure 13) and stiffness decrease in the elastic domain is confirmed after causing the local elastic buckling. The reduction rate in the case (a) is the smallest. This means the influence of this buckling is very small. The reason is that in the case (a), the buckling mode is different from the others. The buckling mode, which occurs not in the joint, is the plate buckling one on the surface of B part (Figure 14). The other modes such as figure 11 are the shear buckling modes in the joint. It is considered the shear one badly affects decrease of bending stiffness.

Table 1. Comparison stiffness in the case of in-plane bending

	Initial (N/mm)	Reduced (N/mm)	Reduction rate %
initial	4021	1909	53%
(a) bulkhead	5160	4490	13%
(b) reinforcement	4456	2525	43%
(c)shape modified	5670	3760	34%

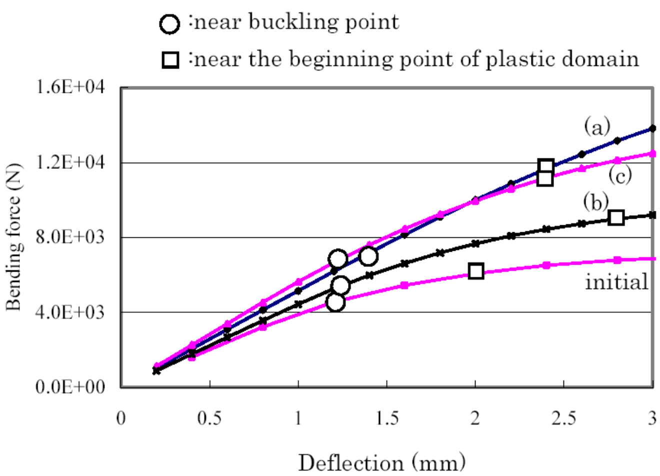


Figure.13 Comparison among different cases

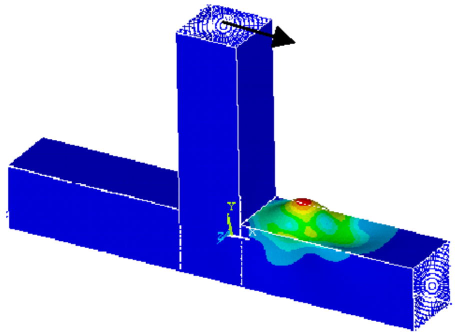


Figure.14 Buckling mode (1)-(a) (F=6.285e3[N])

OUT OF PLANE BENDING

Figure 15 shows deformation of the initial shape at the local elastic buckling load. As shown Figure 16, this deformation by the local elastic buckling occurred at the lower point (F=2.154e3[N]) than the yield point (F=4.14e3[N]). Stiffness decrease in the elastic domain is confirmed after causing the local elastic buckling. In this case, the bending stiffness became about 60 % of the initial one. This decrease is affected by two different type of buckling modes (as shown Figure 17). These are like the plate buckling mode and the share one. However it is difficult to predict this behavior using the theory of effective width since they are not simple ones.

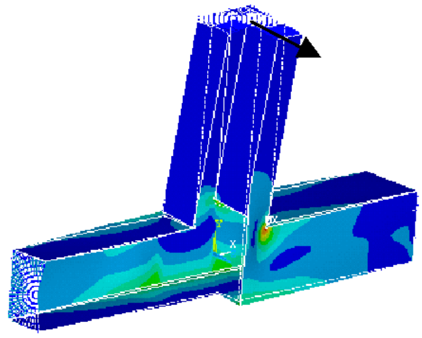


Figure.15 Deformation at the vertical force (F=2.54e3[N])

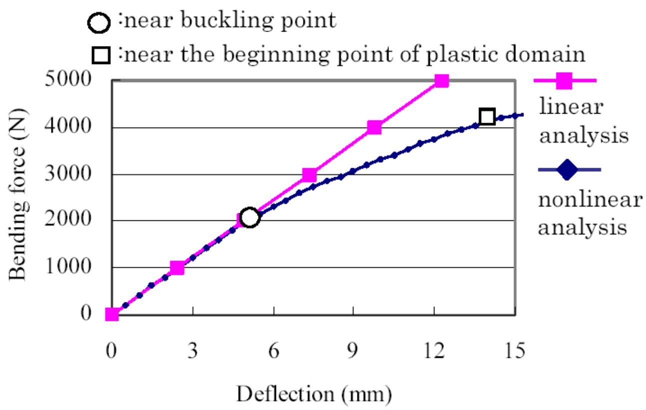


Figure.16 Influence of local elastic buckling under the initial condition

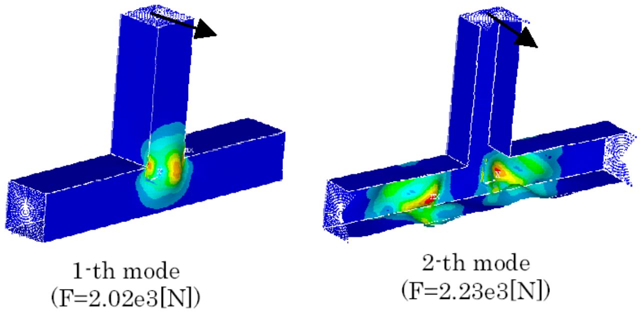


Figure.17 Buckling mode

Table 2 shows the rate of stiffness decrease. In all of cases, the deformation by the local elastic buckling occurs at the lower point than the yield point (Figure 18) and stiffness decrease in the elastic domain is confirmed after causing the local elastic buckling. Each of the reduction rates is the larger than 25 %. The first modes of (a), (b), (c) are similar to the second mode of the initial shape (Figure 17). They belong to torsional buckling modes by a torsional action. It is considered the torsional buckling mode on the surface of B part badly affects decrease of bending stiffness.

Table 2. Comparison stiffness in the case of in-plane bending

	Initial (N/mm)	Reduced (N/mm)	Reduction rate %
initial	407	232	43%
(a) bulkhead	1560	1080	31%
(b) reinforcement	427	317	26%
(c)shape modified	500	367	27%

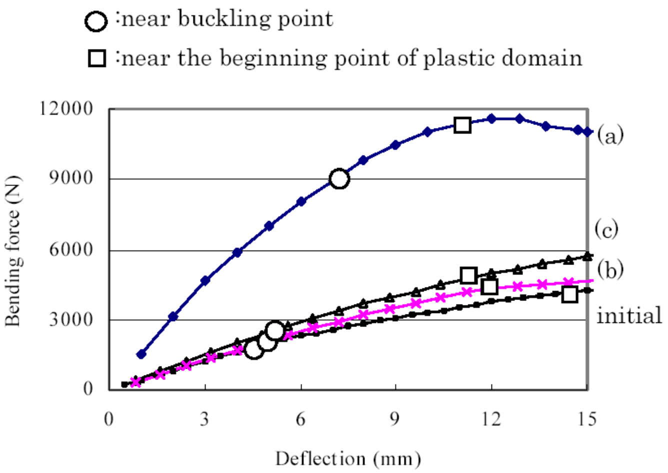


Figure.18 Comparison among different cases

THE WAY OF CONSTRUCTING JOINT MODELS

As I mentioned in the previous section, the buckling behavior of joint structures cannot be easily estimated using the theory of effective width. Because this buckling mode is a shear buckling and a torsional buckling, not a general plate buckling. However this behavior have to be predicted in the concept design process, in order to restrict the stiffness decrease.

On the other hand, we present global-local analysis. At first, we construct joint detailed shell element models about typical joint structures of automotive body and perform various analyses moving design parameters, such as static, dynamics, nonlinear etc. After that, joint models are reduced considering various characteristics obtained by the above analyses.

In this section, after presenting how to construct the liner reduced model using a scalar spring element, we present two type of ways of treating the nonlinear behavior based on local elastic buckling, (1) to find out a joint structure, which does not cause the elastic buckling before the yield point in the local analysis as much as possible and (2) to construct a reduced model including the influence of the local elastic buckling such as a nonlinear spring element.

THE LINEAR REDUCED MODEL

As shown Figure 19, T joint model based on shell elements is constructed. In addition to it, T joint model based on beam elements with rotational spring elements is constructed (Figure 20). The translation connection between two beams is rigid. The latter model is the reduced model of the previous one.

It is assumed that the both edge points of B part are fixed and each of in-plane and out of plane bending load is applied at the edge point of A part. These are unit loads. The rotational spring constant k is calculated so that the displacement of point 3 in the beam model is equal to the one in the shell model.

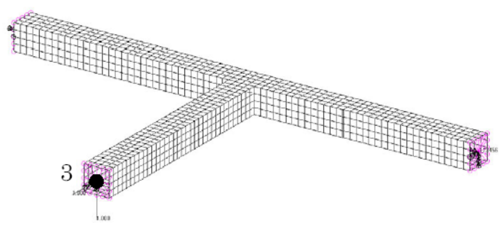


Figure 19 Joint model based on shell elements

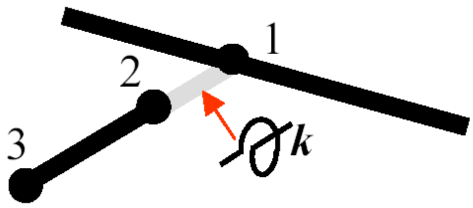


Figure 20 Joint model based on beam elements

The relation among three points (1,2,3) in the beam model with a rotational spring is written as

$$\begin{bmatrix} k'_{11} & k'_{12} & k_{13} \\ k'_{21} & k'_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix}$$

$$\left(k'_{11} = k_{11} + k,\ k'_{22} = k_{22} + k, k'_{12} = k'_{21} = k_{12} - k \right)$$

where k_{ij} is a component of the redued stiffness matrix

k is a rotational spring constant

u_1, u_2 is rotational displacements

u_3 is a displacement

-- (7)

If the displacement at point 3 in the shell model is u^*, k is given as

$$k = \frac{\begin{pmatrix} -k_{12}^2 + k_{11}k_{22} + k_{11}k_{23}^2 u^* + k_{12}^2 k_{33} u^* \\ -k_{11}k_{22}k_{33}u^* + k_{13}^2 k_{22} u^* - 2k_{12}k_{13}k_{23}u^* \end{pmatrix}}{\begin{pmatrix} -k_{11} - 2k_{12} - k_{22} - k_{23}^2 u^* + k_{11}k_{33}u^* \\ +2k_{12}k_{33}u^* + k_{22}k_{33}u^* - k_{13}^2 u^* - 2k_{13}k_{23}u^* \end{pmatrix}} \quad \text{------------ (8)}$$

if $u_3 = u^*$

The linear reduced model of joint modulus in global analysis is obtained as the rotational spring constant. This reduced data is saved in database.

THE WAYS OF TREATING NONLINEAR BEHAVIOR BY LOCAL ELASTIC BUCKLING

In the case of local analysis

The influence of local elastic buckling is studied using the shell model (Figure 19) in the local analysis. If the stiffness decrease is confirmed, we try to find out a joint structure, which does not cause the elastic buckling before the yield point as much as possible. Then as one of results in database, both initial stiffness and modified one by elastic local buckling like Table 1 and 2 are saved.

When a design engineer determines a joint layout, he can obtain a better structure, which isn't badly affected by a local elastic buckling, if he uses this database. He can also calculate another better one from interpolation data, which will be obtained using response surface method.

I would like to show our idea of joint structures that are not badly affected by local elastic buckling.

Shear load is applied on the side surfaces of joints under an in-plane bending force condition. This load causes a shear buckling. In order to restrict it, supporting shear load is important. Inserting bulkhead is good as shown Table 1 (a).

Torsional moment is applied on the surfaces of joints under an out of plane bending force condition. This moment causes a torsional buckling. In order to restrict it, increasing rotational stiffness is important. Figure 21 shows an additional example. In this model, the linear stiffness is made increase by bulkhead. Next, two types of means for local elastic buckling are performed; shape modified and thickness increase. As a result, the initial stiffness is 1600 [N/mm] and the modified stiffness after buckling is 1300 [N/mm]. The reduction rate becomes much smaller (19 %).

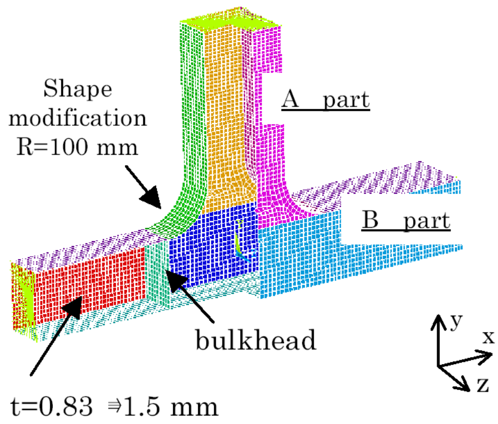


Figure.21 The modified structure

In the case of global analysis

A simple model, which mainly consists of beam elements, is utilized in global analysis. It is so fast and easy to calculate. In this model, joint models are reduced. Then we propose to construct a reduced nonlinear model and perform nonlinear analysis including the influence of the local elastic buckling in joint structures. We think this calculation is not so time-consuming.

As shown Figure 22, we present to approximate the nonlinear stiffness using a bilinear line (K_1, K_2). After that, spring constants (k_1,k_2) is calculated using Eqn (8). We think the nonlinear behavior like Figure 22 can be simulated using the reduced model with a nonlinear spring constant.

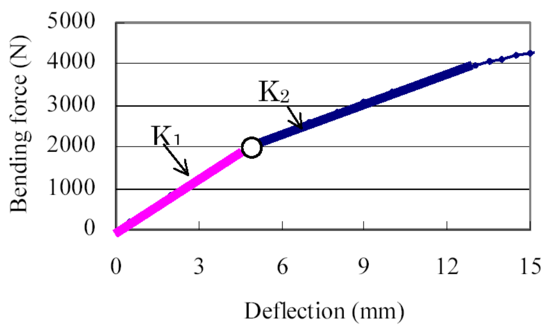


Figure.22 Approximation of the stiffness
(the initial model under out of plane load)

FUTURE WORK

In this section, we show only the concept of treating the nonlinear behavior. As a next step, we would like to create practical database including the influence of the nonlinear behavior after verifying the above concept.

CONCLUSION

We have researched how to design joint structures in the concept design phase using simulation. As a first step, we mainly studied the nonlinear behavior of joints using simple basic structures.

(1) We propose to use the concept of global-local analysis for obtaining a good accuracy and an adequate speed.

(2) The stiffness decrease by local elastic buckling is confirmed using uniform beams. Moreover we simulate the behavior using the theory of effective width.

(3) The stiffness decrease by local elastic buckling is also confirmed in joint structures. Shear buckling and tosional buckling causes this behavior.

(4) We propose the way of constructing joint models. We present two type of ways of treating the nonlinear behavior based on local elastic buckling:

to find out a joint structure, which does not cause the elastic buckling before the yield point in the local analysis

to construct a reduced model including the influence of the local elastic buckling such as a nonlinear spring element.

REFERENCES

1. Nishigaki, H., Nishiwaki, S., and Kikuchi, N., 2001, “First Order Analysis – New CAE Tools for Automotive Body Designers”, Proceedings of SAE 2001 World Congress, Detoroit, USA, 2001-01-0768
2. El-sayed, M. E. M., 1989, “Calculation of joint spring rates using finite element formulation”, Computers and Structures 33(4), 977-981
3. Kim, Y. Y., Yim, H. J., and Kang, J.H., 1995, “Reconsideration of the joint modeling technique: in a box-beam T-joint”, SAE, 951108, pp.275-279
4. Kim, Y. Y., and Kim, H. J., 2002, “New accurate efficient modeling techniques for the vibration analysis of T-joint thin-walled box structures”, Solid and Structures, Elsevier Science Ltd., 39(2002), 2893-2909
5. Lee, K., and Nikolaidis, E., 1992, “A two-dimentional model for joints in vehicle structures”, Computers and Structures, 45(4), 775-784
6. Marin, D. C. and Diewald, T. E., 1998, “Automotive Steel Design Manual”, American Iron and Steel Insutitute and Auto/Steel Partnership, pp.3.1.1-3.1.52.
7. Wei-Wen Yu., 1972, “Cold-formed Steel Structures”, Mcgraw-hill book company
8. 2003, “Seminar note of ANSYS structural nonlinear analysis”, cybernet system

CONTACT

The corresponding author of this paper is Yasuaki Tsurumi. He is now working at Toyota Central R&D Labs., Inc. His e-mail address is e0927@mosk.tytlabs.co.jp.