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Author:		Antonino Vicente Rico				Date:		17/07/2013									
FEM	X	HAND		LIN		NOLIN		BUCK	X	FAT		STATIC		COMP	X	MET	X
BUCKLING WITH LINEAR GAPS																	

1. INTRODUCTION

There are some situations in which it is desired to simulate contacts between different parts of a structure. Multiple methods can be used to analyze these kind of situations, for example the use of CGAP element in nonlinear analysis (SOL 106). But in order not to perform non-linear analysis, it is possible to use linear gaps with linear analysis (SOL 101). With this method, NASTRAN iterates to obtain the existing contacts in the deformed configuration. Therefore, the analysis is in some way being transformed into a non-linear analysis.

The problems appear when buckling analysis of structures with linear gaps are performed. The reasons for these problems are that in general neither the behavior of the structure with this kind of model nor the physical behavior of the structure is well-known.

2. LINEAR GAPS IMPLEMENTATION

In order to implement linear gaps into a static subcase, it is necessary to include some cards into the bulk data section. Firstly, "PARAM,CDITER,50" has to be included. This PARAM requests the iteration process. The maximum number of iterations is given by the number behind CDITER, which in this case is 50.

Once the PARAM is included, it is necessary to create two scalar points for each desired linear gap. These scalar points will represent the value of the initial gap, and the value of the gap on the deformed condition.

One of the scalar points is included into the r-set using the SUPORT card. The r-set are commonly used when the structure is loaded with accelerations and it is not constrained. As the SUPORT card can be used for different analysis (inertia relief for example), it is not possible to join different kind of those analyses (inertia relief + linear gaps). Therefore, if a linear gaps analysis is desired, "PARAM,INREL" must not be included. The scalar point which has been included into the r-set is the one used to perform the iterations and it represents the final gap value.

The other scalar point, as it has been mentioned previously, represents the initial gap measure which does not change in the iteration process. Therefore to set the initial gap

BUCKLING WITH LINEAR GAPS

value a SPC card is used. The initial gap value must be placed into the displacement field of the SPC.

Finally, to complete the linear gap, it is necessary to impose the relations between the real nodes and the scalar points. To do that, the equation which represents the relations between the vertical displacements of the nodes and the initial and final gap measures are introduced into a MPC card.

It is important to notice that the SPC and MPC must be called in the correspondent subcase definition (on the case control section), otherwise linear gaps will not be taken into account.

For better understanding of the way in which linear gaps are implemented, the NASTRAN code and the explanation of the analysis of the structure shown on Figure 1 are going to be explained.

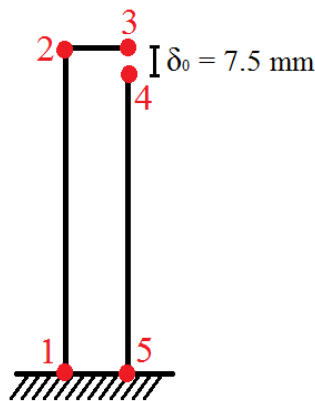



Figure 1

It is desired to impose a linear gap between nodes 3 and 4 in order to simulate possible vertical contacts. If the geometry of the structure is known, the initial gap can be set. In this case the initial gap is equal to 7.5 mm. It is important to notice that the initial gap is not necessary equal to the distance between nodes 3 and 4. The reason of this is that the beam from node 2 to 3 can have offset and also the section has some thickness.

With the previous data it is possible to generate the NASTRAN code, which is shown below.

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BUCKLING WITH LINEAR GAPS																	

```

SOL 101
CEND
...
SUBCASE 1
  SPC = 101106
  MPC = 101106
...
BEGIN BULK
$111111122222223333333344444444555555556666666677777777
...
PARAM,CDITER,50
PARAM,CDPCH,YES
PARAM,CDPRT,NO
...
SPOINT 1000 1001
SUPPORT 1000 0
SPC 101106 1001 0 7.5
MPC 101106 4 2 1. 3 2 -1.
      1000 0 1. 1001 0 -1.
...


```

As it can be seen, two scalar points have been created (1000 and 1001). The first one has been included into the r-set. Therefore it will represent the final value of the gap. The other scalar point (1001) will store the initial value of the gap. To do that, a 7.5 value has been inserted into the SPC card.

Finally, the MPC which represent the relation between the scalar points and the real nodes has to be included into the code. In the example which is being studied the vertical displacements of nodes 3 and 4 are the DOFs which are required into the displacement equation. In this case the vertical displacement of both nodes are given by the second DOF. The relation between the DOF of both nodes and the initial gap and final gap values is given by equation (1.0).

$$V_4 - V_3 + \delta_f - \delta_0 = 0 \quad (1.0)$$

In the same way a linear gap has been implemented into the NASTRAN code, it is possible to implement as much as desired. But it is important not to forget to call the SPC and MPC

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BUCKLING WITH LINEAR GAPS																	

of the linear gaps on the case control section.

Before jumping to next chapter it is important to clarify some parameters of the previous code. As it can be seen “PARAM,CDPCH,YES” and “PARAM,CDPRT,NO” have been introduced into the code. The first parameter requests for a punch file in which the r-set scalar points with contact are reported. The second parameter requests not to report the forces and stresses which do not satisfy the constraints.

3. PROBLEMS WITH LINEAR GAPS IN LINEAR BUCKLING.

There are three main ways in which it is possible to analyze the behavior of a structure with linear gaps.

- Include linear gaps in static and buckling subcases.
- Include only linear gaps in static subcase.
- Not include linear gaps in any subcase.

Errors exits in the three ways, but they are different and the results can be conservative or not.

The three different ways and the related problems are going to be explained in the following sub-chapters.

3.1. Linear gaps in static and buckling subcases.

In order to consider the linear gaps in both subcases it is necessary to introduce the SPC and MPC calls in both subcases.

With this process the static subcase will be solved as a normal case with linear gaps. That is, the linear gaps condition will be set after some iterations to satisfy the equilibrium equations.

It is important to remind that the displacements of the static subcase are used to obtain the differential stiffness matrix in the buckling subcase.

As it is known the differential stiffness matrix is required for buckling analysis. This matrix represents the variation of the stiffness in a structure as the load increases. For example,

BUCKLING WITH LINEAR GAPS

imaging you have a ruler. If you apply on it a tension load, the transversal stiffness increases with regards to null load. On the other hand, if you apply a compression load, the transversal stiffness decreases, being possible to reach the buckling (null transversal stiffness).

But the problem arises when the buckling analysis is performed, because there is no iteration process to determine if the linear gaps are opened or closed. By default, all linear gaps will be closed in the linear buckling analysis.

In linear buckling it is not reasonable to have some linear gaps opened and some closed if there is a simple contact condition. The reason of this is that the buckling modes are eigenvectors that can be multiplied by any number. Therefore it is possible to change the sense of the buckling mode. This fact means that a buckling mode cannot be constrained in one side but not in the other. A buckling mode is or is not constrained, but cannot be constrained on one sense and not on the other (the buckling is a linear approach).

For better understanding of this concept, the buckling problem of the structure shown on Figure 2 is going to be analyzed

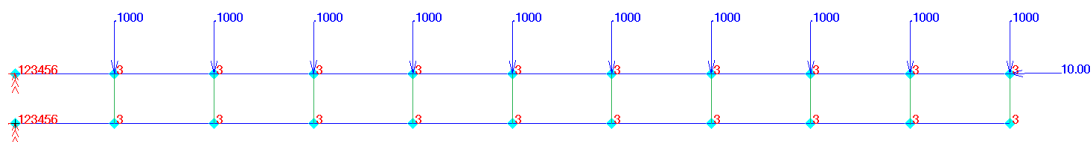


Figure 2

In the model of the structure there are 10 linear gaps (green lines) which represent the vertical contact of the different parts of the structure. In the static subcase the linear gaps condition will be set as a function of the structure properties, loads and geometry. For the previous structure, the beam centers distance 50 mm. Both beams have a 20 mm radius circular section. Therefore the initial gap is 10 mm. Performing the static analysis of the structure, it is possible to obtain the deformed configuration that is shown on Figure 3. In this condition the last gap of the structure is closed while the others are opened, but with a gap measured lower than 10 mm.

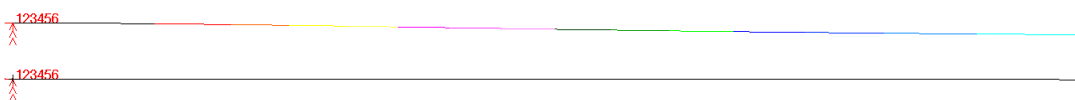


Figure 3

BUCKLING WITH LINEAR GAPS

For the buckling analysis all linear gaps are closed, but there is no contact. The meaning of not being in contact but being closed is that the initial gap is set as the gap for the full analysis. The first buckling mode of the structures considering linear gaps is given on Figure 4.

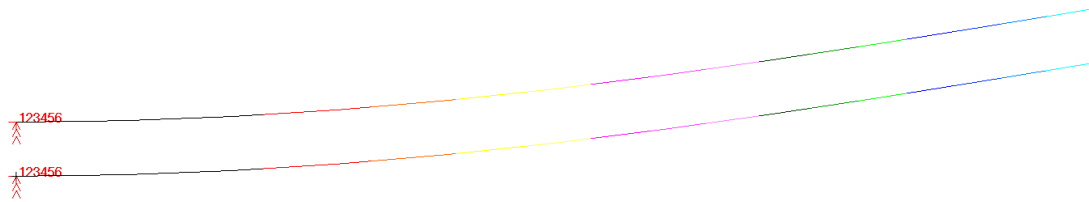


Figure 4

As it has been said the gap value is constant and equal to the initial gap value. This can be noted on Figure 4.


In this case the buckling mode obtained does not correspond with a real buckling mode or at least not one of the first buckling modes of the structure. If the initial gap would be null the previous buckling mode would represent a real buckling mode of the structure, but not the first one.

The problem in this case is that the buckling mode is being constrained with the linear gaps. The constraint imposes a joint condition between both beams even if there is no contact. This condition gives as a result a stiffness increment in the upper beam. Depending on the structure configuration and the desired buckling mode, the results obtained can be correct or not.

With the purpose of identifying the different cases in which the results are correct or not, some examples are presented below. Usually the desired mode is the first buckling mode discarding the rest of buckling modes. Due to this reason only the cases in which the first buckling mode is obtained are going to be taken into account in the examples.

Imposing linear gap in static and buckling cases gives correct solutions if it is modeled a structure with contact in both sides. A typical example of this is a fastener joint.

For fastener joints between two parts there is no problem due to the axial force is given by the fastener. But in case of having three or more pieces joined with fasteners, problems appear if the joint is modeled properly. A properly model means a model in which the central parts have not a movement in the axial direction of the fastener

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BUCKLING WITH LINEAR GAPS																	

constrained. Therefore, as the axial movement is not constrained, it is necessary to place linear gaps in the model.

On this kind of structures the buckling analysis can be performed properly with linear gaps in both, static and buckling subcases. These kind of models are correct because in the real structure the different parts are approximately in contact all the time.

3.2. Linear gaps in static subcase.

In this case linear gaps are considered only in the static subcase. To do that the SPC and MPC calls must be placed into the corresponding static subcases.

With this model, the static subcase is solved in the same way as in the previous sub-chapter, but the buckling analysis is performed with no linear gaps. This gives as a result a constraint of the differential stiffness matrix. But the stiffness matrix of the structure in the buckling subcase does not take into account the linear gaps, therefore the stiffness would be lower than in the previous sub-chapter.

The results of this kind of model are more conservative than the results of the model which considers linear gaps in the buckling analysis, and they are quite similar to the real results.

If the structure from Figure 2 is analyzed with linear gaps only in the static subcase the static deformed configuration will be exactly the same as the one shown on Figure 3. But the first buckling mode would be different with regards to the one obtained in the previous sub-chapter. In this case the first buckling mode is shown on Figure 5.

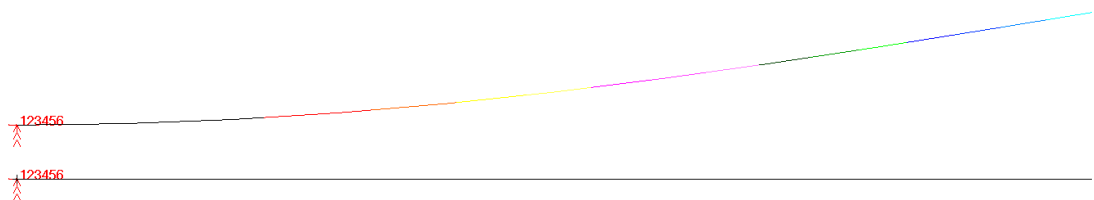



Figure 5

As it can be noted, the buckling mode only affects the upper beam. This happens because there are loads only in the upper beam and there is no linear gap in the buckling subcase.

Comparing the eigenvalues from this model and the one which considers linear gaps in

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BUCKLING WITH LINEAR GAPS																	

the buckling analysis, a significant difference can be noted. As it has been mentioned in the previous sub-chapter, when the linear gaps are considered in the buckling analysis, the buckling mode is not usually one of the first buckling modes. Even when the buckling mode obtained is topologically similar to the real buckling mode, some divergences remain. These divergences can be conservative or not. Therefore if a more conservative analysis is desired, it would be better not to consider the linear gaps in any subcase.

3.3. Structure without linear gaps.

In this model any kind of linear gaps are considered, therefore there are no changes of stiffness with regards to the original structure without linear gaps. As a consequence of this, the most conservative results are obtained.

Following with the example of the structure shown on Figure 2, the following results can be obtained. The deformed configuration for the static subcase is shown on Figure 6.

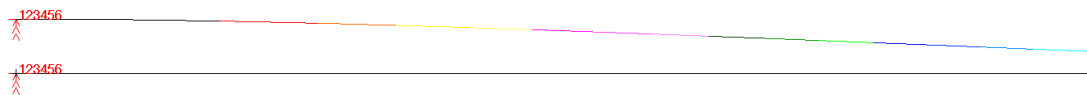


Figure 6

As it can be seen the right end of the upper beam has a vertical displacement higher than 10 mm, therefore in the real life there would be a contact between both parts of the structure. This deformation is used to determine the differential stiffness matrix which in general will be different with regards to the one considering linear gaps.

Analyzing the buckling subcase, a buckling mode as the one shown on Figure 5 would be obtained. But due to the differences between the static subcases considering or not the linear gaps, the eigenvalue and eigenvector would be different. In case the deformed configuration would have the linear gaps opened, buckling modes would be the same between model corresponding to 3.2 and 3.3 sub-chapter.

Therefore as it has been said, this kind of model reports the most conservative results. But these results does not necessary correlate with the real results due to the high level of conservatism.

BUCKLING WITH LINEAR GAPS

4. PRACTICAL EXAMPLE.

In this chapter the results of a structure that has been analyzed on the three different ways are going to be reported. The main aim of this example is a better understanding of the influence of the linear gaps in the static and buckling subcases.

The structure that is going to be analyzed is a squared plate welded on its corners with a reticular structure. The reticular structure consist on a bar on each side of the plate and two bars joined in the middle which divide the squared shape into four equal squares.

The structure can be seen on Figure 7 in which the bars are represented with blue lines, and the green lines are the sides of the CQUADs of the plate.

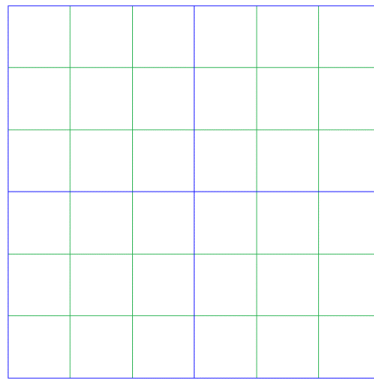


Figure 7

Due to the plate is only welded on its corners, it would be necessary to insert linear gaps in the other coincident nodes from the model. The boundary condition consist on a simply support constraint on the reticular structure boundary. As a consequence of placing linear gaps in the boundary nodes it would not be possible to directly constraint the vertical DOF of the boundary nodes. The reason of this is the incompatibility between MPC and SPC in the same DOF. Therefore, to avoid that problem, springs with high stiffness will be used to constraint the vertical movement. These springs will have a clamped node on one side, and the vertical DOF of the reticular structure on the other side. To avoid problems with the springs it would be better to have null length.

BUCKLING WITH LINEAR GAPS

Once the boundary conditions are imposed, it is time to impose the loads for the analysis. In this case an overpressure and suction loads have been selected.

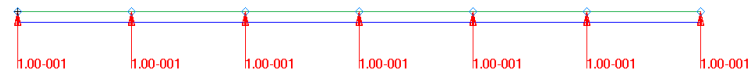
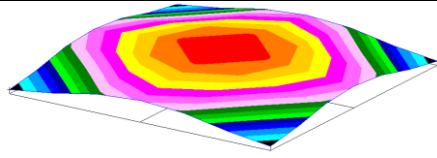
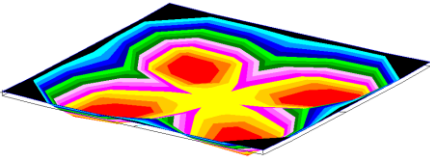
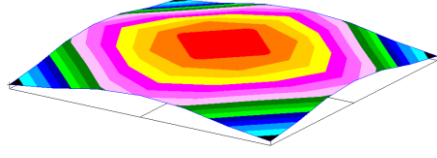
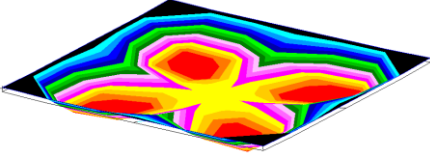
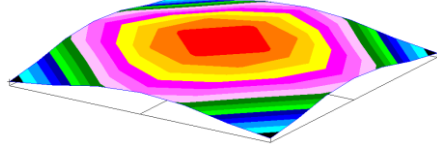
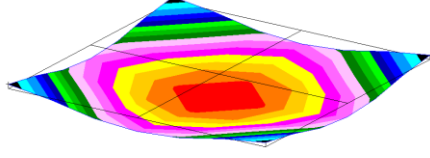


Figure 8 Suction Load

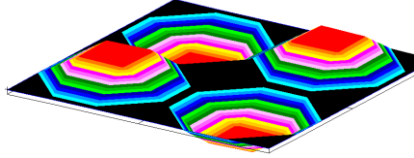
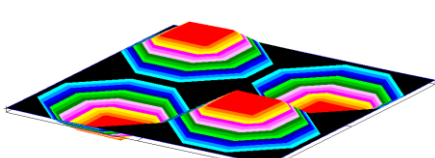
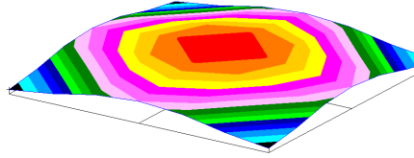
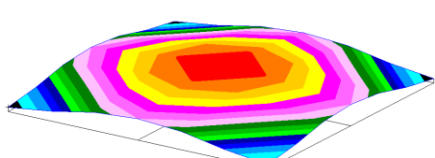
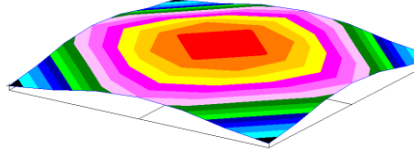
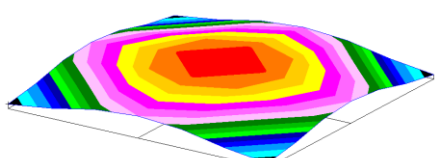


Figure 9 Overpressure Load

The structure has been analyzed with the three different kinds of linear gaps consideration. Its results are presented below.

		Deformed configuration	
		Suction Load	Overpressure Load
Linear gaps in static and buckling subcases.			
Linear gaps in static subcase.			
Structure without linear gaps.			
Buckling modes and eigenvalues			
		Suction Load	Overpressure Load

BUCKLING WITH LINEAR GAPS

Linear gaps in static and buckling subcases.		
	$\lambda = -54.74$	$\lambda = 69.91$
Linear gaps in static subcase.		
	$\lambda = -6.32$	$\lambda = 8.07$
Structure without linear gaps.		
	$\lambda = -6.32$	$\lambda = 6.32$

The previous results can be related with the conclusions that have been explained throughout the previous chapters. The value of the load for all the cases is the same except the sing. Therefore the eigenvalues can be compared directly.

It is possible to see that in the buckling cases in which the linear gaps are considered, the buckling modes are constrained. This constraint is not influenced by the linear gaps condition on the static subcase.

When the linear gaps are only taken into account in the static subcase, it can be seen that the buckling mode is not constrained by the linear gaps. Therefore the eigenvalue associated is quite lower than the eigenvalue associated with the buckling subcase in which linear gaps are considered.

In case of having linear gaps only in the static subcase, a variation of the differential stiffness matrix can be noted regarding the static subcase with no linear gaps. This difference can be seen in the eigenvalues of the overload pressure. On the other hand, when the linear gaps are opened in the static subcase, the previous difference does not exist as can be noted in the suction load cases.