ANALYSIS OF SHELL STRUCTURES USING MSC/NASTRAN'S SHELL ELEMENTS WITH SURFACE NORMALS

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ABSTRACT

MSC/NASTRAN's lower order shell elements TRIA3, QUAD4, TRIAR, and QUADR are some of the most frequently used shell elements in the finite element market. The performance and quality of MSC's shell elements have been tested over a long period of time, but there is still potential for improvement. It has been reported that moderately thick shell elements with transverse shear flexibility are too soft in twist for cases where additional bending and membrane forces are active. In addition, spurious out-of-plane rotations have been reported. The behavior occured only in very few practical problems and it did not appear in the MacNeal-Harder standard test problems. Unique surface normals at grid points are introduced in MSC/NASTRAN Version 68.2 to improve the behavior of the shell elements. The improvement of shells with normals is shown.

1. Introduction

Grid point normals for lower order shell h-elements are introduced in Version 68.2. The normals are implemented for the QUAD4, TRIA3, QUADR, and TRIAR shell elements. First, we describe the problems which we had with our shell elements before we introduced shell normals. Then we explain how normals improve the shell element behavior. Details of the user interface for shell normals are provided. Two small test examples and two real world problems show how much the shell elements improve when normals are used.

2. Background

It has been reported that our shell elements are too flexible in some examples where a combination of twisting, bending and membrane forces are active and transverse shear flexibility is turned on. Convergence studies showed that the deformations did not converge when the mesh is refined. It was concluded that the elements did not transfer twisting moments correctly in curved shell models. The behavior occured in flat elements with transverse shear flexibility turned on. In Version 68 and in earlier Versions, we made the following recommendations to improve the results.

1. Turn off transverse shear flexibilty, MID3=0 on the PSHELL entry. The problem converged but the results became too stiff without transverse shear flexibility.
2. Add stiffness to the out-of-plane rotation of the shell by using a large value of K6ROT. The results became stiffer. We got reasonable answers with values around K6ROT=1000. The results were sensitive with respect to the K6ROT value.

Following our recommendations, the user could produce satisfactory results for the given load case. The sensitivity of the results with respect to the magnitude of K6ROT has been disturbing. MSC needed to implement more rigourous changes in the formulation of the lower order shell elements to fix the problem.

It has been concluded that unique surface normals at grid points are necessary to improve the behavior of the lower order shell elements. The author of MSC/NASTRAN's shell elements proposed a method to use unique grid point normals in the existing quadrilateral and triangular elements. The method has been implemented in Version 68.2 of MSC/NASTRAN. The original formulation of MSC/NASTRAN's shell elements [1] is retained.

Another problem has been reported in shell elements with drilling degrees of freedom. QUADR and TRIAR elements produced incorrect bending moments in curved shells. Grid point normals are used to improve the results of the QUADR and TRIAR elements for curved geometry.

3. Generation of Grid Point Normals and User Interface

An algorithm has been developed to generate unique normals at grid points. In the finite element model of a curved shell, local normals of adjacent shell elements have different directions. An average normal is generated at each grid point so that the angles between the average normal and all the local normals of the adjacent shell elements are minimized, see Figure A in the Appendix. The algorithm can handle doubly curved surfaces. The generated grid point normals may be not normal to the element plane. In finite element models with different types of elements, normals are only generated at grid points which connect at least one QUAD4, TRIA3, QUADR, or TRIAR element.

In cases where the model has real edges, unique grid point normals are not necessary. The grid point normal is deleted if the angle between the average normal and each local normal of adjacent elements exceeds a user specified tolerance. Furthermore, the user may input a grid point normal which will be used regardless of the geometry at that grid point. User specified normals have priority over generated normals. The QUAD4, TRIA3, QUADR, and TRIAR elements use grid point normals if at least one grid point normal in the element exists.

The user interface for shell normals has been designed so that there is minimal impact on the existing interface. The tolerance for edges is specified with the parameter SNORM.

The tolerance also turns the automatic generation of normals on and off. The user may specify normals with the SNORM Bulk Data entry. The interface is described in the Appendix. By default, grid point normals are not generated. The capability of grid point normals is available in all structured solution sequences for linear problems.

4. Example Problems

4.1. Remarks to Standard Test Problems

All examples of the MacNeal-Harder standard test problems [2] are run with and without normals. In examples with flat geometry, the results are identical within machine precision whether shell normals are used or not. In examples with curved geometry, the differences between the results with and without shell normals are under 0.1 % in the deformations. We conclude that the standard test problems do not uncover the deficiencies of shell elements without normals. In the following, we present only examples where shell normals improve the results.

4.2 Hook

The hook is a curved strip clamped at one end and loaded at the other end with an in plane shear load, see Figure 1. The problem was presented by one of our clients [3]. The example is selected here because the model is simple and the improvements with shell normals are obvious.

All the lower order elements without normals (QUAD4, QUADR, TRIA3, and TRIAR) fail to converge for subsequent mesh refinements if transverse shear flexibility is turned on. The results for QUAD4 and QUADR elements are shown in Table 1. The problem converges if transverse shear flexibility is turned off. However, the results without transverse shear flexibility are too stiff. For QUAD4 and TRIA3 elements, we have an alternative way to achieve convergence by using a high value of the K6ROT parameter.

The K6ROT parameter is a scaling factor for stiffness in the 6th degree of freedom. The results depend on the magnitude of K6ROT.

The results with shell normals show that the normals do not stiffen the model. Both QUAD4 and QUADR converge to the right value when we use normals and transverse shear flexibility is turned on (MID3=1). The shell elements without transverse shear flexibility (MID3=0) behave too stiff with or without normals.

Furthermore, the shell normals make the results less sensitive with respect to the K6ROT parameter. We keep the mesh size constant and vary the parameter K6ROT. The model without shell normals becomes stiffer when we increase the K6ROT value. In the model with shell normals, the results do not change for a wide range of K6ROT values. We recommend to use PARAM K6ROT 0. and PARAM AUTOSPC YES. In linear analysis, the K6ROT parameter is not needed if we have shell normals.

4.3 Pressurized Cylinder with Free Ends

The problem in Figure 2 was presented as customer support request [4]. The problem is a simple pressurized cylinder with free ends. The shell has a constant membrane stress state. We model a segment of size θ and half of the height. We take 4 elements in cylinder z-direction. Appropriate SPCs are introduced along the three inner boundaries. Grid point normals are defined at the boundaries in radial direction. We investigate the convergence of the shell elements for different angles θ of the segement. The radial displacements at the free end is shown in Table 3. The QUAD4 converges with and without normals, the normals do not change the results. The QUADR without normals fails, see the deformed shape in Figure 3. The QUADR with normals gives the same good results as the QUAD4. The normals provide the correct direction of the drilling degrees of freedom in the QUADR.

4.4 Bracket

A typical bracket was formed from sheet metal. It is thin (t/L = approx. 4/300), and has several holes and bent tabs. Large areas are relatively flat. It was modeled with QUAD4 and TRIA3 elements with transverse shear flexibility (MID3 > 0). PARAM AUTOSPC YES was used, and PARAM K6ROT was zero. When static loads are applied to the model, large rotations are observed at some grid points. Figure 4 is an "arrow" plot, where the arrow size is proportional to the rotation. The rotations appear mostly in relatively flat areas. There was concern that stresses and displacements resulting from such an analysis would be useless.

Using a K6ROT value of 1.E3 gets rid of the rotations, but could the stresses be trusted? With the new shell normals capability we can now use another technique. PARAM SNORM 15, PARAM AUTOSPC YES, and PARAM K6ROT 0 were used. The rotation vector results are shown in figure 5. Using the same scale factor for arrow length, it is seen that the rotations were greatly reduced. Examination of stresses and translations show very close answers for all three methods of analysis. In this case the rotations were spurious, and could have been ignored. Also, the previous recommendation of large K6ROT worked well.

4.5 Frame Structure

A typical frame structure of joined beam sections is used to illustrate another case where large rotations were observed. The 37,196 grid points have 223,176 total degrees of freedom (g-set). There are 35,320 QUAD4 and TRIA3 elements in the model. No transverse shear flexibility was used (MID3 = 0). Figure 6 is an arrow plot of rotations found using static analysis. Large rotations were observed at scattered points.

Here again, using K6ROT makes the spurious rotations go away. The shell normals were turned on (with K6ROT=0), and figure 7 shows much reduced rotations. Stresses and displacements were observed to be close for all three methods of analysis.

It is interesting to observe the relationship between K6ROT (adds penalty stiffness), SNORM (aligns singularity) and the AUTOSPC feature. Below is a table of the number of degrees of freedom in the analysis set, a number proportional to total run time, and a measure of matrix conditioning. Using grid point normals improves the matrix conditioning by 4 orders of magnitude.

K6ROT	SNORM	A-SIZE	RUN TIME	MAX RATIO
0.	0.(off)	191,425	598	1.5E+8
1000.	0.(off)	212,634	713	3.0E+4
0.	15.	182,102	648	4.5E+4

5. Conclusions

The results of the MacNeal-Harder standard test decks do not change for shells with normals compared to shells without normals. The standard test set covers most of the problems which occur in real world models. Elements that pass the standard test set are expected to give quality results and MSC/NASTRAN's elements have proven to meet these expectations.

Unique grid point normals improve the results for some selected curved shell problems in which twist in combination with bending and membrane forces are active. We decided that the improvements are important enough to be delivered to our clients. We summarize the improvements due to shell normals.

1. The twisting moments are transmitted correctly in curved shells. Transverse shear flexibilty does not cause divergence.
2. The condition number of the stiffness matrix is better.
3. The K6ROT parameter is not needed in small deformation problems if we turn AUTOSPC on. In case if K6ROT is used, we have experienced that results get less sensitive with respect to the magnitude of the K6ROT parameter.

4. The shell elements with drilling degrees of freedom, QUADR and TRIAR, improve in curved membrane applications.

In V68.2, grid point normals are not default. We recommend the following parameter combination to activate the use of grid point normals,

PARAM AUTOSPC YES
PARAM K6ROT 0.(default in linear analysis)
PARAM SNORM 15. (nondefault)

At this time, we have limited experience with the performance of grid point normals. Grid point normals have to be generated and they cause more calculations in the element stiffness. In our examples, the overall run time did not increase significantly when we used grid point normals.

Acknowledgement

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References

1. R.H. MacNeal, " A Simple Quadrilateral Shell Element," *Computers & Structures*, Vol.8, pp175-183, 1978.
2. R.H.MacNeal and R.L.Harder, " A Proposed Standard Set of Problems to Test Finite Element Accuracy ", *Journal of Finite Elements in Analysis and Design*, Vol.1, 3- 20, (1985).
3. MSC/NASTRAN client service request CSR3387, reported error for QUAD4, by I.Raasch, BMW Munich, November 1986
4. MSC/NASTRAN client service request CSR 4540, reported error for QUADR, by D. Liebe, MSGmbH Munich, 1989.

t= 2.0

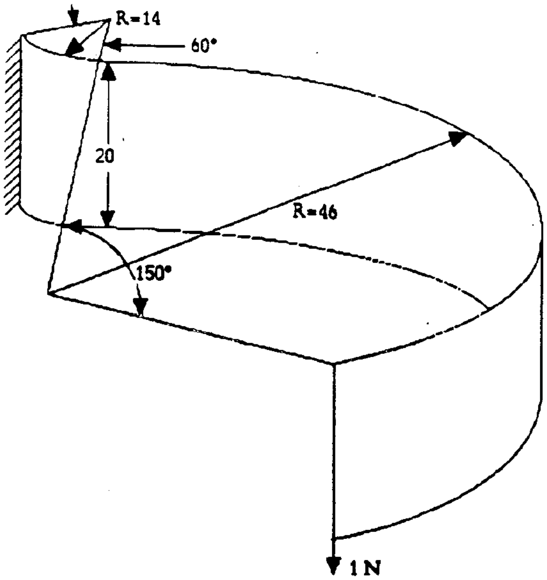

Figure 1. Hook from [3].

Displacement at tip in direction of the shear force T3 normalized with 5.012

	mesh	without normals		with normals	
		MID3=0	MID3=1	MID3=0	MID3=1
QUAD4	1x9	0.9153	0.9465	0.9096	0.9238
	3x17	0.9453	1.0559	0.9385	0.9829
	5x34	0.9508	1.2595	0.9436	0.9845
	10x68	0.9500	2.0443	0.9428	0.9933
	20x136	0.9490	4.7891	0.9417	1.0002
QUADR	1x9	0.9138	0.9333	0.9108	0.9250
	3x17	0.9425	1.0029	0.9387	0.9831
	5x34	0.9493	1.0635	0.9437	0.9846
	10x68	0.9494	1.3014	0.9429	0.9933
	20x136	0.9487	2.1779	0.9417	1.0002

Parameter values are K6ROT=0., AUTOSPC = YES,
MID3=0 no transverse shear flexibility,
MID3=1 with transverse shear flexibility

Table 1. Hook, displacement at tip.

Displacement at tip in direction of the shear force T3 normalized with 5.012

K6ROT	without normals	with normals
0.e+0	4.7891	1.0002
1.e+0	4.4447	1.0002
1.e+2	1.4468	1.0002
1.e+4	1.0078	1.0002
1.e+6	1.0002	1.0001

MID3=1 with transverse shear flexibility, AUTOSPC=YES for K6ROT=0.

Table 2. Hook, displacement at tip for 20x136 QUAD4 mesh and different K6ROT values.

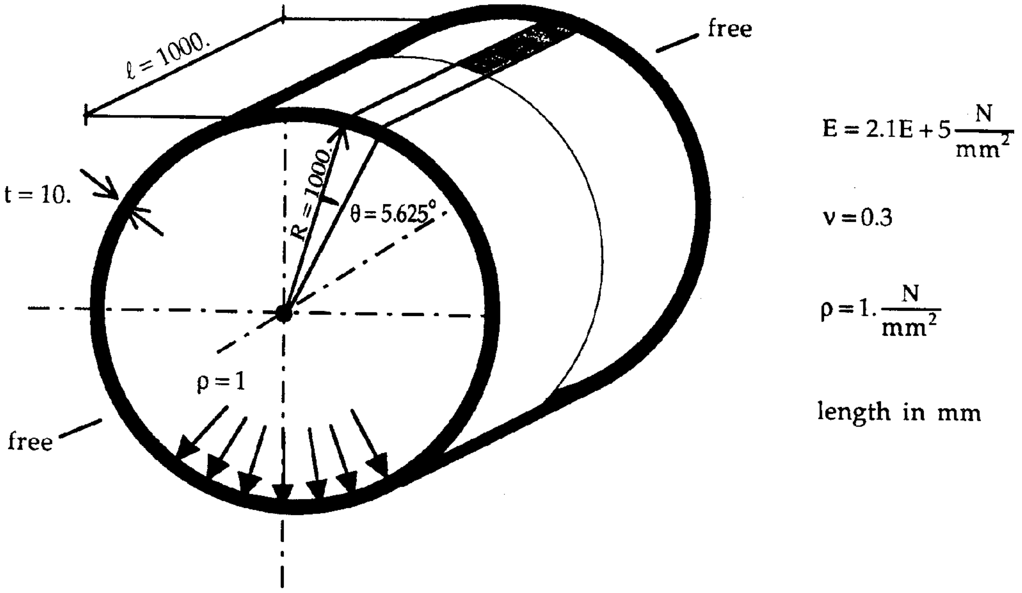

Figure 2. Segment of pressurized cylinder with free ends from [4].

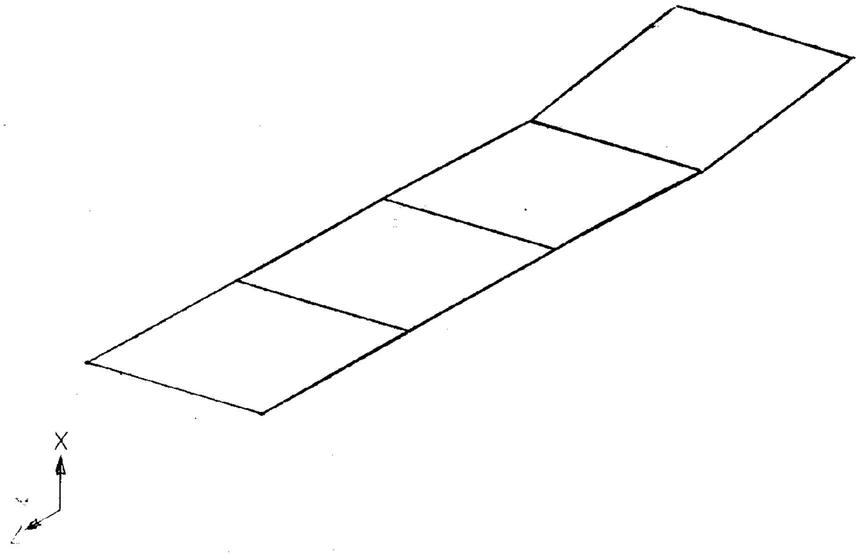

Figure 3. Pressurized cylinder, false deformation of the QUADR in V68.

Radial displacement normalized with exact value of 0.47619.
4 elements in longitudinal direction,
different angle of the segment

	QUAD4	QUADR	
θ	with and without normals	without normals	with normals
22.50000	0.980786	1.413001	0.980786
11.25000	0.995186	1.422556	0.995186
5.62500	0.998796	1.421999	0.998796
2.81250	0.999700	1.419106	0.999700
1.40625	0.999926	1.417126	0.999926

Table 3. Pressurized cylinder with free end, displacement in radial direction at the free end.

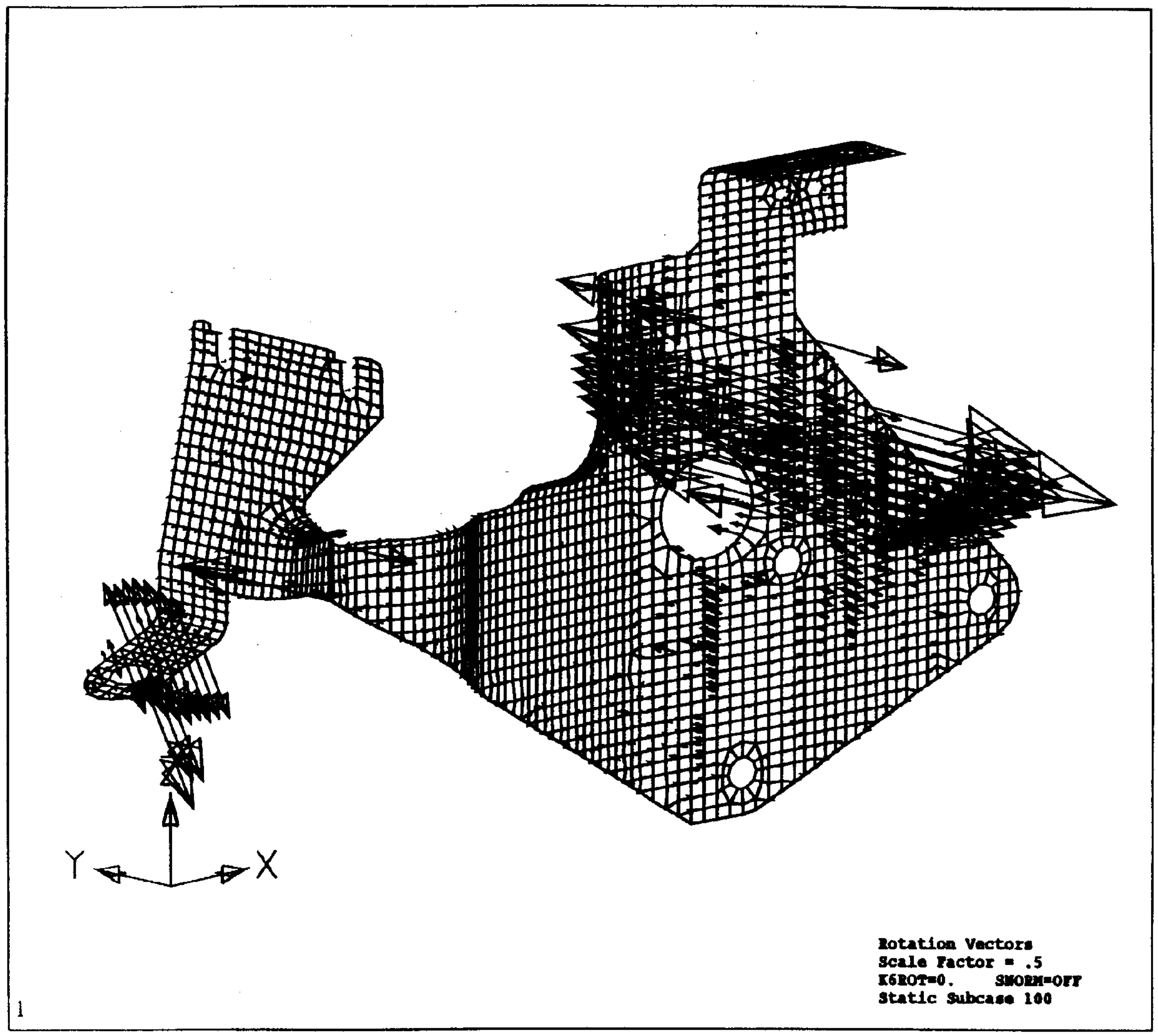

Figure 4. **Bracket without** normals, AUTOSPC YES, K6ROT= 0.

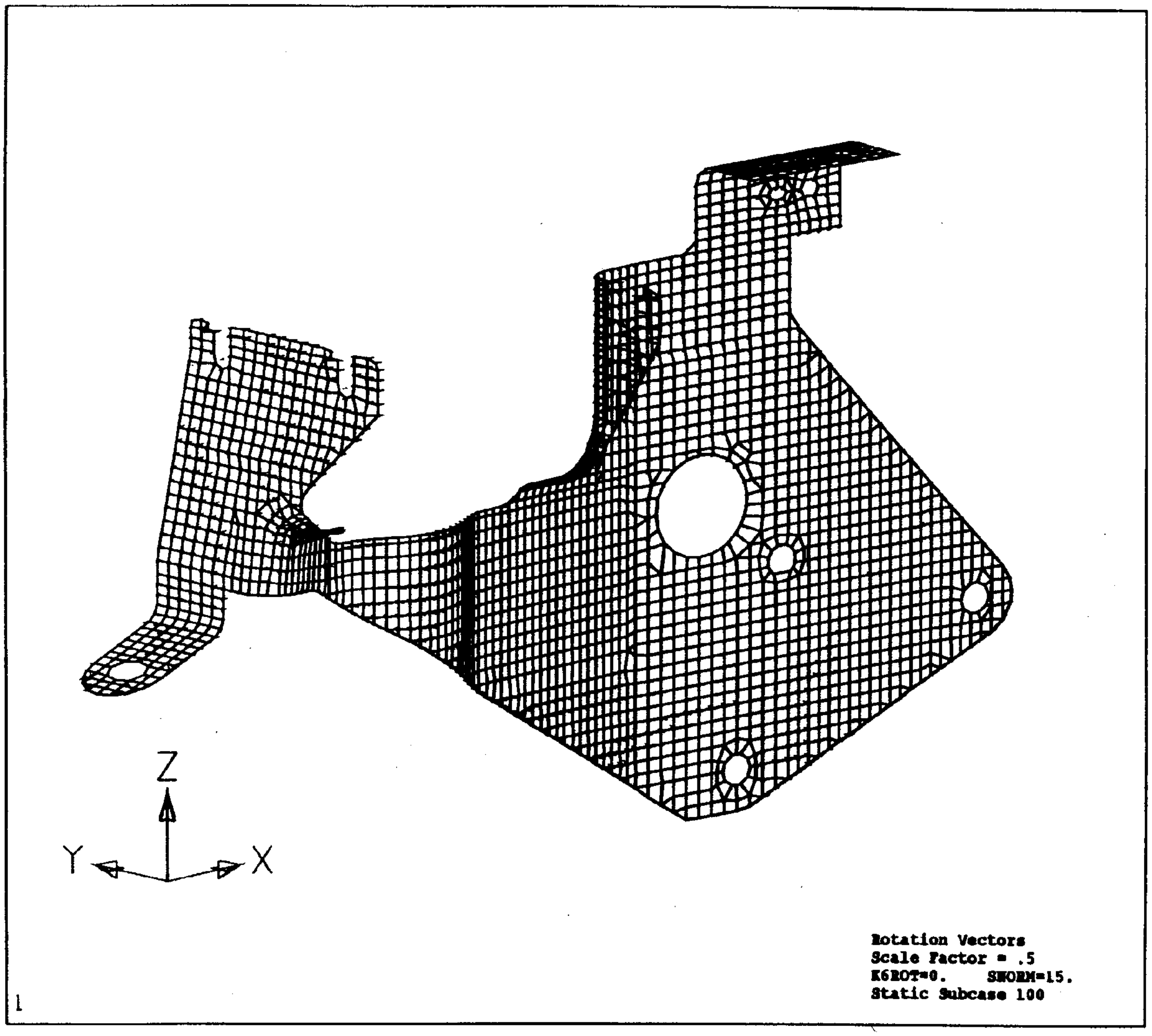

Figure 5. Bracket with normals, AUTOSPC YES, K6ROT= 0.

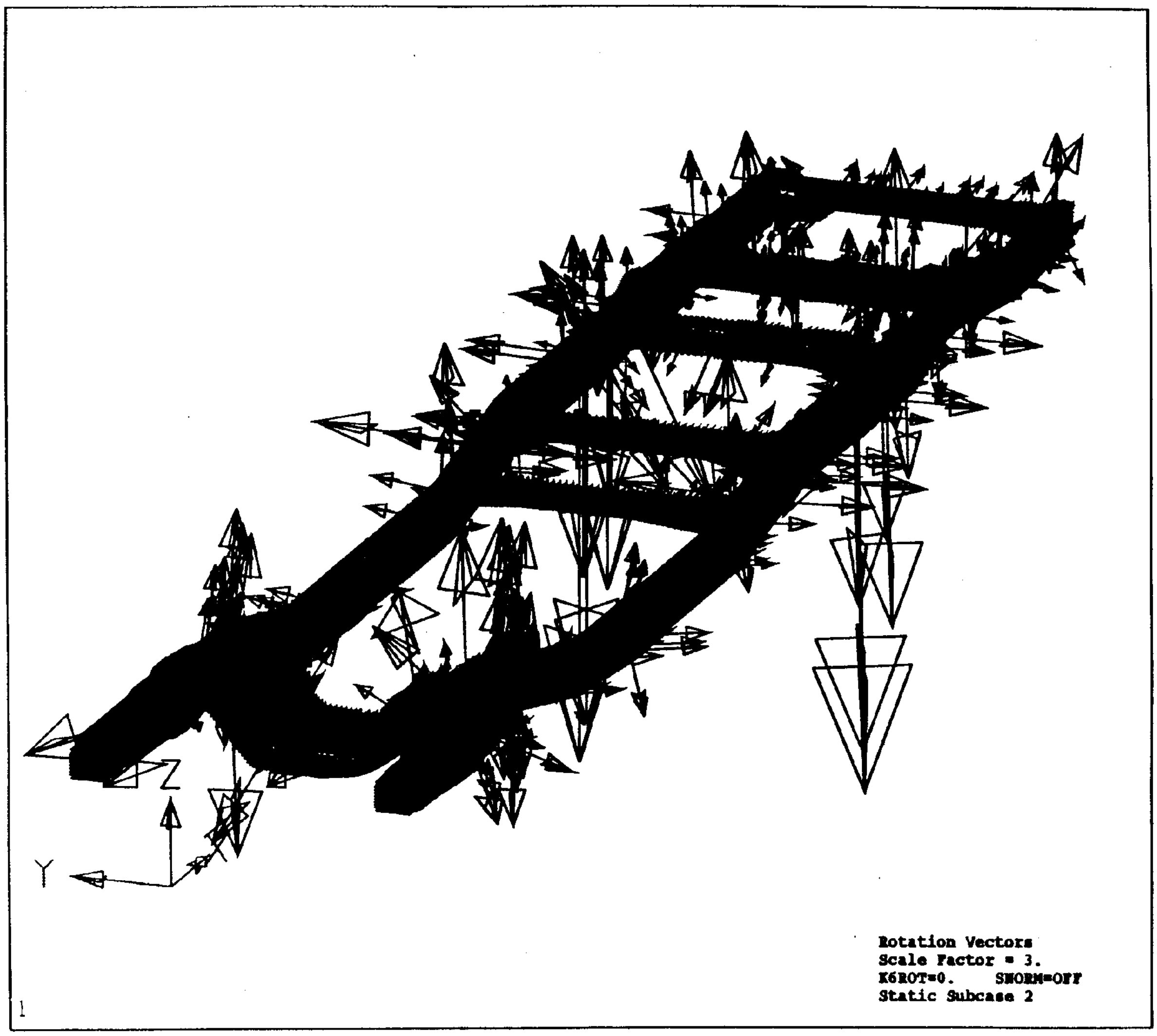

Figure 6. Frame Structure **without** normals, AUTOSPC YES, K6ROT= 0.

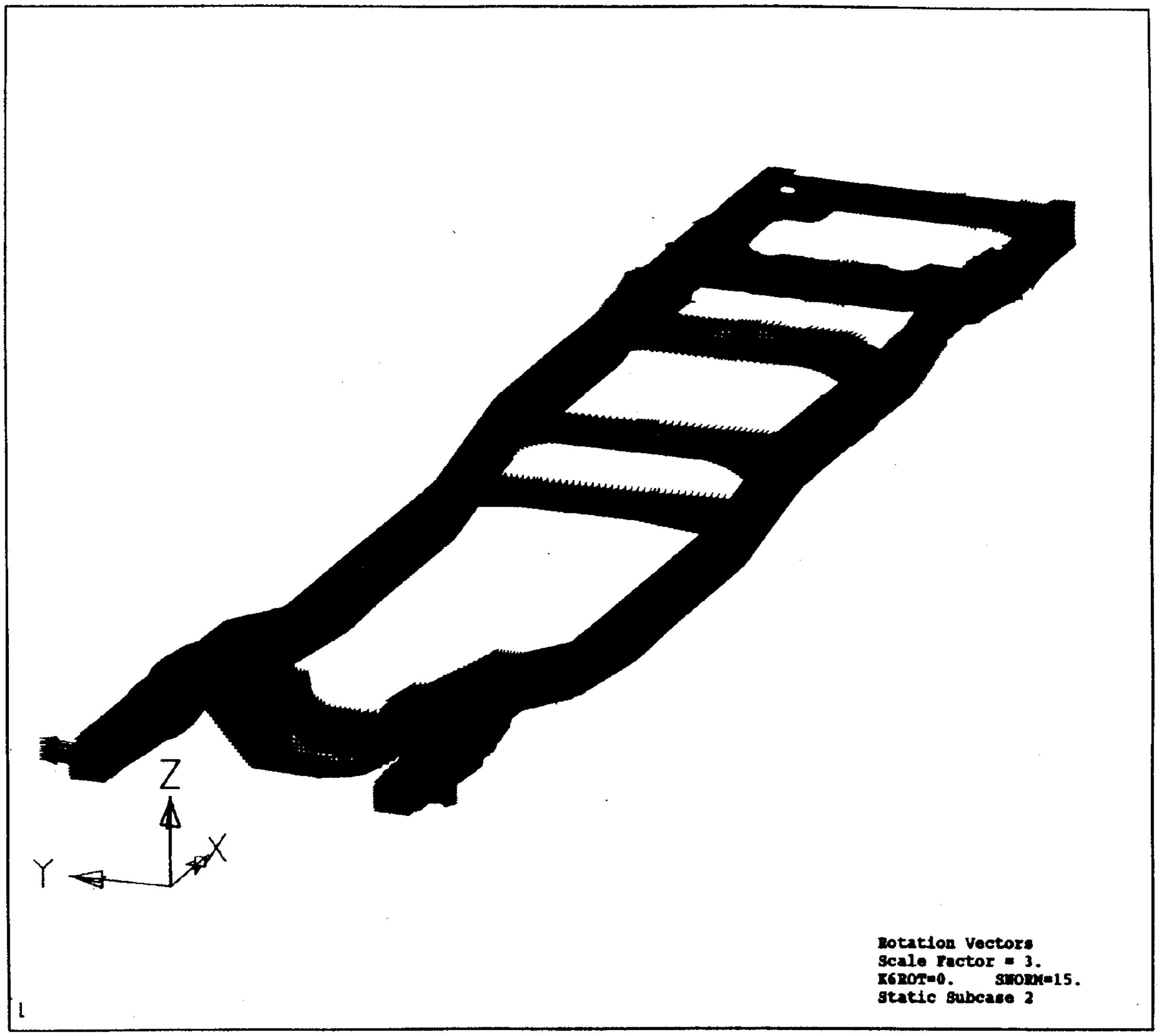

Figure 7. Frame Structure **with normals**, AUTOSPC YES, K6ROT= 0.

APPENDIX: User Interface for Shell Normals

New Bulk Data Entry

SNORM Surface normal vector at grid point

Defines a surface normal vector at a grid point for QUAD4, QUADR, TRIA3, and TRIAR shell elements

Format:

SNORM	GID	CID	N1	N2	N3				

Example:

SNORM	3	2	0.	-1.	0.				

Field	Content	
GID	Unique grid point identification number	required
CID	Identification number of coordinate system in which the components of the normal vector are defined, default is basic (0 or blank)	integer or blank
N1, N2, N3	coordinates of normal, default is 0., 0., 0.	real

Remarks

1. The SNORM Bulk Data Entry overwrites all given requests for shell normals, for example, it overwrites the generated grid point normal. The internal generation of unique grid point normals is activated with the parameter SNORM, see parameter description.

2. The normal is used in the QUAD4, QUADR, TRIA3, and TRIAR shell elements. For all other elements, the normal is ignored.

3. The components of the normal vector are in basic by default. If a CID > 0 is specified, the components of the normal are in the coordinate ssytem CID. For example, if the displacement coordinate system of the grid point is specified, CID$=$ CD, then the components of the normal are in the global system.

4. It is not required that the three components of the normal form a unit vector.

Parameter SNORM

PARAM, SNORM, β_{TOL}

SNORM activates or deactivates the generation of unique grid point normals for adjacent shell elements, see Figure A. Unique grid point normals are generated for the QUAD4, TRIA3, QUADR, and TRIAR elements. The grid point normal is the average of the local normals from all adjacent shell elements including QUAD8 and TRIA6 elements. If grid point normals are present, they are used in all element calculations of the QUAD4, TRIA3, QUADR, and TRIAR elements.

β_{TOL}	Tolerance in degrees, real, default = -1.
$\beta_{TOL} > 0$	unique grid point normals are generated if each angle β between the grid point normal and each local normal of the adjacent shell elements is smaller than the tolerance $\beta \leq \beta_{TOL}$. SNORM Bulk Data Entries overwrite a generated normal.
$\beta_{TOL} = 0$	the generation of grid point normals is turned off. The user can define normals with Bulk Data Entries SNORM.
$\beta_{TOL} < 0$	Grid point normals are not generated. SNORM bulk data entries are ignored.

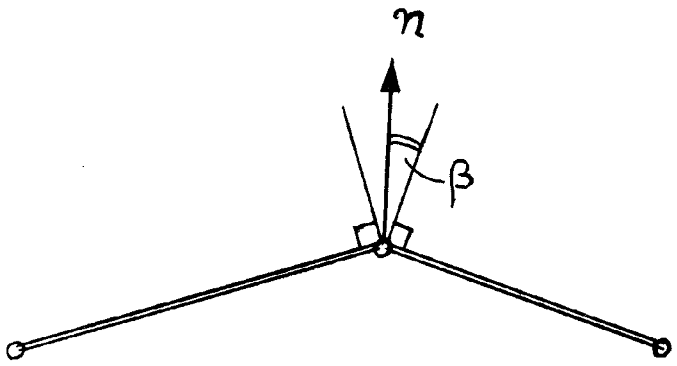

Figure A. Unique grid point normal for adjacent shell elements.

Parameter SNORMPRT

PARAM, SNORMPRT, iopt

SNORMPRT activates a print out of all grid point normals of the model in basic coordinates.

iopt	switch to print out normals, integer, default= -1
iopt ≤ 0	no output
iopt= 1	print out to the punch file *.pch
iopt= 2	print out to the print file *.f06
iopt= 3	print out to the punch and print file *.pch and *.f06