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D O C U M E N T

document title/ titre du document

CATALOGUE OF BENCHMARK CASES FOR THE ANALYSIS OF INFLATABLE STRUCTURES

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TABLE OF CONTENTS

1 INTRODUCTION

This document presents a catalogue of benchmark cases for the analysis of inflatable structures. Its goal is to define benchmark cases, which will be used to determine suitable numerical methods and software for the analysis of inflatable structures.

2 LOADS, ENVIRONMENT AND ANALYSES

This chapter presents the types of loads, environment and analyses to be considered during the life of a space structure.

2.1 Loads

The types of loads to be considered are:

Pressure: Internal or external, it can be constant or varying (pressurisation, pressure decay)
Static: Static accelerations (translational and/or rotational)
Dynamic: Dynamic accelerations (translational and/or rotational)
Thermal: Constant temperature or temperature gradient along the structure
Local: Punctual force applied to membrane or local load applied to structure (including restrain force during deployment)
Shock: Shock spectrum applied to the structure
Impact: Hypervelocity impact on the structure (MMOD)

2.2 Environments

The types of environment to be considered are:

Ground: air and gravity
Space: vacuum and μ-gravity

2.3 Output

The types of output to be considered are:

Displacements: Depending of the case: static, cinematic, dynamic, thermo-elastic or wrinkling pattern and amplitude
Stress/strain: Depending of the case: static, cinematic, dynamic, thermo-elastic and including the effect of wrinkling
Eigenmodes: Eigenvalue and eigenvectors
Buckling: Eigenvalue and buckling shape
Shock: Assessment of the damage due to shock
Impact: Assessment of the damage due to impact

3 LIFE CYCLE

In this chapter, each step of the life cycle of an inflatable structure is presented with the associated environment and applied loads.

Life step	Environment	Loads	Remark
Manufacturing	G	Ther, Loc	Seams, welds, …
Handling/packaging	G	Loc, Pres	Venting for packaging
Qualification testing	G	Stat, Dyn, Sh, Ther, Pres, Loc	Vacuum tests may be considered Two configurations: folded/deployed
Launch	G → S	Stat, Dyn, Sh, Ther, Pres	Similar to folded qualif. tests Ext. pressure decay
Deployment	S	Pres, Ther, Loc	Restrain forces to be considered
Deployed, pressurised, unrigidised	S	Pres, Ther, Stat, Imp	AOCS loads
Deployed, vented, rigidised	S	Ther, Stat, Imp	AOCS loads

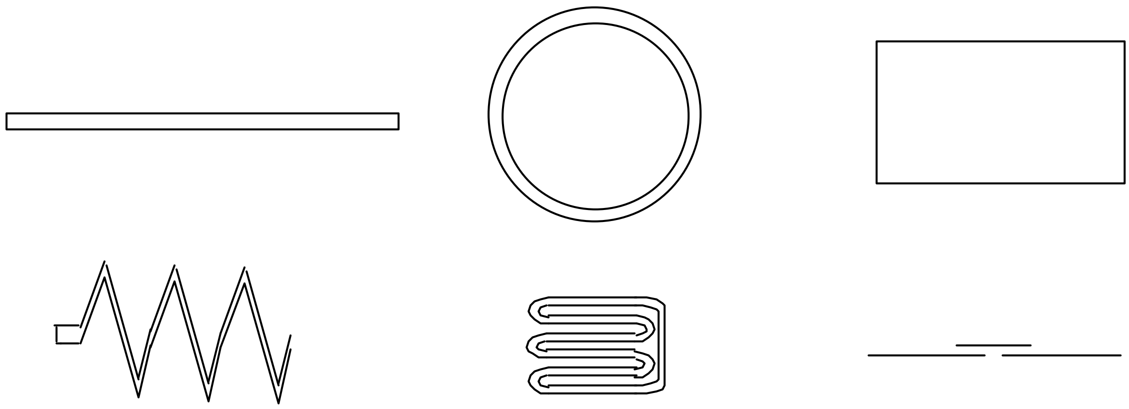
4 ANALYSES REQUIREMENTS

The following table shows the analyses requirements along the life cycle

Life step	Disp	Str	Eig	Buck	Sh	Imp
Manufacturing		X				
Handling/packaging	X	X		X		
Qualification testing:						
static folded	X	X				
dynamic folded	X	X	X			
shock folded					X	
thermal folded	X	X				
deployment	X	X				
static deployed	X	X		X		
dynamic deployed	X	X	X			
thermal deployed	X	X	X	X		
Launch	X	X	X		X	
Deployment	X	X		X		
Deployed, pressurised, unrigidised	X	X	X			X
Deployed, vented, rigidised	X	X	X	X		X

5 BUILDING BLOCKS

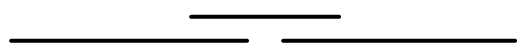
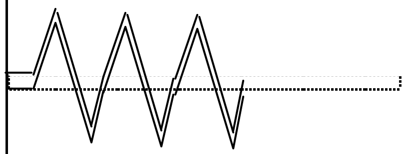
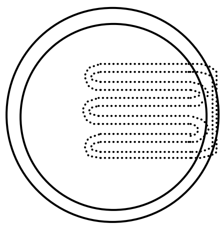
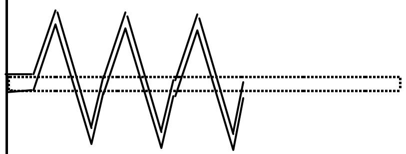
The following building blocks shall be considered for an inflatable structure:

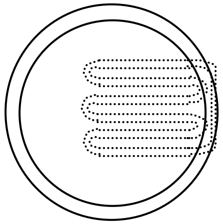
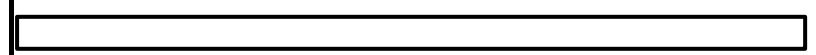
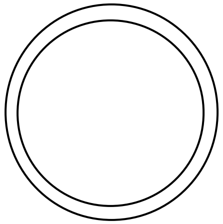


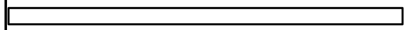
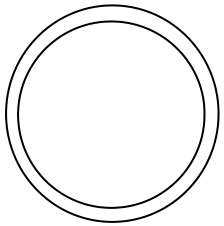
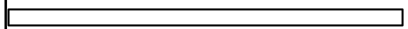
Beam (deployed, stowed)   Torus (deployed, stowed)   Membrane (stretched, joint)

6 DEFINITION OF BENCHMARK CASES

Based on the information presented in the previous chapters, it is possible to define a list of benchmark cases for the numerical analyses of inflatable structures.

#	Name	Building block	Loads	Environment	Analyses	Softwares	Priority
1	manuf. stresses		Ther	G	Str	NASTRAN SAMCEF ABAQUS Std ANSYS	III
2	deployment of a beam. Subcases: - Z-folding - accordion - rolled		Pres, Ther	1- G 2- S	Disp, Str	DYTRAN ABAQUS Exp LS-DYNA RADIOSS PAM-CRASH	I
3	deployment of a torus. Subcases: - Z-folding - rolled		Pres, Ther	1- G 2- S	Disp, Str	DYTRAN ABAQUS Exp LS-DYNA RADIOSS PAM-CRASH	I
4	controlled deployment of a beam. Subcases: - Z-folding - accordion - rolled		Pres, Loc, Ther	1- G 2- S	Disp, Str	DYTRAN ABAQUS Exp LS-DYNA RADIOSS PAM-CRASH	I

#	Name	Building block	Loads	Environment	Analyses	Softwares	Priority
5	controlled deployment of a torus. Subcases: - Z-folding - rolled		Pres, Loc, Ther	1- G 2- S	Disp, Str	DYTRAN ABAQUS Exp LS-DYNA RADIOSS PAM-CRASH	I
6	analyses of a deployed pressurised beam		Pres, Stat, Ther, Loc, Dyn	1- G 2- S	Disp, Str, Buck, Eig	NASTRAN SAMCEF ABAQUS Std ANSYS DYTRAN ABAQUS Exp	I
7	analyses of a deployed pressurised torus		Pres, Stat, Ther, Loc, Dyn	1- G 2- S	Disp, Str, Buck, Eig	NASTRAN SAMCEF ABAQUS Std ANSYS DYTRAN ABAQUS Exp	I
8	analyses of a stretched membrane. Subcases: - point loading - edge loading		Stat, Loc, Dyn, Ther	1- G 2- S	Disp, Str, Eig	NASTRAN SAMCEF ABAQUS Std ANSYS	I

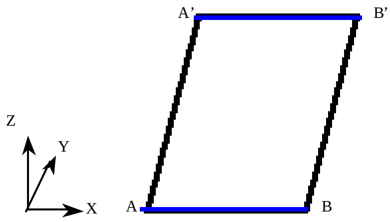
#	Name	Building block	Loads	Environment	Analyses	Softwares	Priority
9	analyses of a deployed vented beam		Ther, Stat, Loc, Dyn	1- G 2- S	Disp, Str, Eig, Buck	NASTRAN SAMCEF ABAQUS Std ANSYS	I
10	analyses of a deployed vented torus		Ther, Stat, Loc, Dyn	1- G 2- S	Disp, Str, Eig, Buck	NASTRAN SAMCEF ABAQUS Std ANSYS	I
11	MMOD impact on pressurised beam		Pres, Imp	S	Imp	AUTODYN DYTRAN	III

<table>
<tr><th colspan="2">Inflation of a flattened tube made of isotropic material</th><th>2-1</th></tr>
<tr><td colspan="3">Objectives</td></tr>
<tr><td colspan="3">Predict the final shape of an inflated tube.</td></tr>
<tr><td colspan="3">Particular issues</td></tr>
<tr><td colspan="3">Modelisation of thin membranes.</td></tr>
<tr><td colspan="3">Input</td></tr>
<tr><td>Geometry, boundary conditions and loading
The tube can be:
- closed at both ends 2-1a,
- opened at both ends 2-1b,
- a mix of these two 2-1c</td><td colspan="2">Material properties

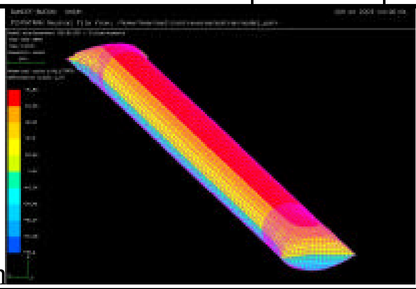
The tube is made of Mylar® or polyamide film.</td></tr>
<tr><td colspan="3">Output</td></tr>
<tr><td colspan="3">Final shape of the tube (in particular at the creases and closed end).
Stresses of the membranes elements.</td></tr>
<tr><td colspan="3">References</td></tr>
<tr><td>Analysis
1) Dynamics of Large Reflectors Dynamic Analysis Study for an Inflatable Space Rigidized Structure Type of Reflector (ESTEC final report 8455/89/NL/PM(SC))</td><td colspan="2">Testing
1) Dynamics of Large Reflectors Dynamic Analysis Study for an Inflatable Space Rigidized Structure Type of Reflector (ESTEC final report 8455/89/NL/PM(SC))</td></tr>
</table>

Geometry					**2-1a**
Stowed Structure			**Deployed Structure**		
Width	m	0.235	Diameter	m	0.150
Total Length	m	3.0	Length	m	3.0
Thickness	m(10^{-3})	0.05	Thickness	m	N/A
Volume	m^3	N/A	Volume	m^3	N/A

Sketch



Skretch



Properties					
Material: Mylar®			**pressure applied directly on the elements**		
Type	-	**92A**	Density	kg m^{-3}	N/A
Density	Kg m^{-3}	1390	cp	J kg^{-1} K^{-1}	N/A
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	N/A
Maximum Strain	-		Temperature	K	N/A
Young Modulus	Pa (10^6)	4805.2	Remarks		
Poisson's Ratio	-	0.3			

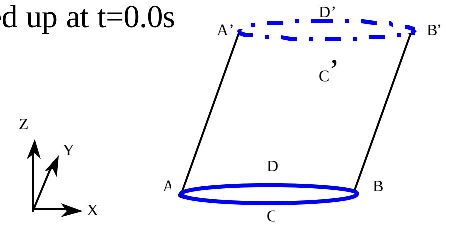
Loads and Boundary Conditions				
Loads applied on the elements			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	6065	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	N/A	Line A-B	clamped
Inflation Time	sec	0.2	Line A'-B'	free
Remarks: pressure variation				
			Remarks isostatic Boundary Conditions	

Time(s)	0.0	0.1	0.11	0.2
Value (Pa)	0.0	1000	6065	6065

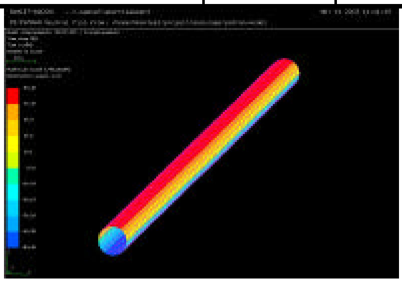
Environment		
Environmental Pressure	Pa	0
Gravity	m s^{-2}	0
Temperature	K	N/A

Geometry					**2-1b**
Stowed Structure			**Deployed Structure**		
Width	m	0.157	Diameter	m	0.1
Total Length	m	3.0	Length	m	3.0
Thickness	m (10^{-3})	0.05	Thickness	m	N/A
Volume	m^3	N/A	Volume	m^3	N/A

Sketch: the points C and D (C' and D') are mixed up at t=0.0s



Sketch



Properties					
Material: Mylar®			**pressure applied directly on the elements**		
Type	-	**92A**	Density	kg m^{-3}	N/A
Density	Kg m^{-3}	1390	cp	J kg^{-1} K^{-1}	N/A
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	N/A
Maximum Strain	-		Temperature	K	N/A
Young Modulus	Pa (10^6)	4805.2	Remarks		
Poisson's Ratio	-	0.3			

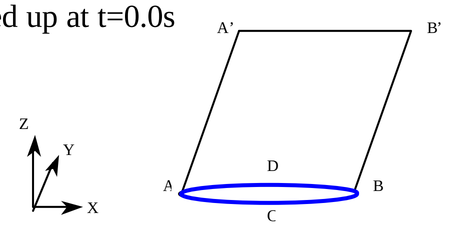
Loads and Boundary Conditions				
Loads applied on the elements			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	5000	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	N/A	Lines A-B, B-C, C-D,	Y-axis
Inflation Time	sec	1.0	Points A and B	Z-axis
Remarks: pressure variation			Points C and D	X-axis
			Remarks: isostatic Boundary Conditions	

Time(s)	0.0	0.01	0.1	1.0
Value (Pa)	0.0	5000	5000	5000

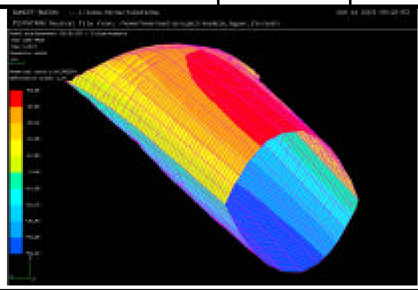
Environment		
Environmental Pressure	Pa	0.0
Gravity	m s^{-2}	0.0
Temperature	K	N/A

Geometry					**2-1c**
Stowed Structure			**Deployed Structure**		
Width	m	0.157	Diameter	m	0.1
Total Length	m	0.5	Length	m	0.5
Thickness	m (10^{-3})	0.1	Thickness	m	N/A
Volume	m^3	N/A	Volume	m^3	N/A

Sketch: the points C and D (C' and D') are mixed up at t=0.0s



Sketch



Properties					
Material: Polyamide			**pressure applied directly on the elements**		
Type	-		Density	kg m^{-3}	N/A
Density	Kg m^{-3}	1130	cp	J kg^{-1} K^{-1}	N/A
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	N/A
Maximum Strain	-		Temperature	K	N/A
Young Modulus	Pa (10^6)	2000	Remarks		
Poisson's Ratio	-	0.33			

Loads and Boundary Conditions				
Loads applied on the elements			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	5000	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	N/A	Point A	X-Y-Z-axis + MX
Inflation Time	sec	0.01	Point B	Y-Z-axis + MX
Remarks: pressure variation			Line A'-B'	free
			Remarks: isostatic Boundary Conditions	

Time(s)	0.0	0.01
Value (Pa)	0.0	5000

Environment		
Environmental Pressure	Pa	0.0
Gravity	m s^{-2}	0.0
Temperature	K	N/A

S

Deployment of a Z-folded beam made of isotropic material | **2-2**

Objectives

Predict the deployment and the final shape of an inflated Z-folded beam.

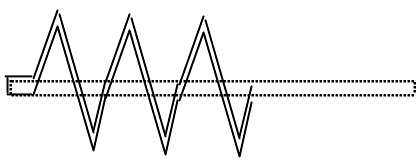
Particular issues

Modelisation of thin shells and large displacement dynamic analysis.

Input

Geometry, boundary conditions and loading

A Z-folded beam.
The beam is fixed at one end.
An internal pressure is applied to inflate the beam.



Material properties

The tube is made of a polyamide film.

Output

deployment envelope (vs. time) and final shape.

References

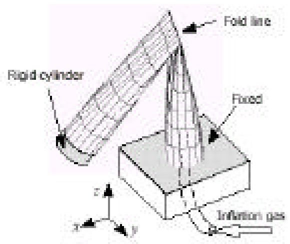
Analysis

2) Dynamics of Large Reflectors Dynamic Analysis Study for an Inflatable Space Rigidized Structure Type of Reflector (ESTEC final report 8455/89/NL/PM(SC))
3) Deployment Dynamics of Inflatable Tube (Y Miyazaki, M Uchiki, AIAA-2002-1254)
4) Deployment Simulation of Ultra-Lightweight Inflatable Structures (JT Wang, AR Johnson, AIAA-2002-1261)

Testing

1) Dynamics of Large Reflectors Dynamic Analysis Study for an Inflatable Space Rigidized Structure Type of Reflector (ESTEC final report 8455/89/NL/PM(SC))
2) Deployment Dynamics of Inflatable Tube (Y Miyazaki, M Uchiki, AIAA-2002-1254)

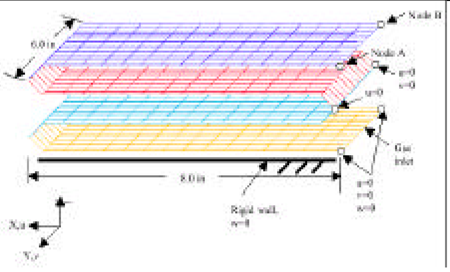
Geometry					**2-2a**
Stowed Structure			**Deployed Structure: folded tube**		
Width	m		Diameter	m	$2.4x10^{-2}$
Total Length	m		Length	m	0.2
Thickness	m		Thickness	m	$1.04x10^{-4}$
Volume	m^3		Volume	m^3	N/A
Sketch			Sketch		



Properties					
Material			**Gas: N2**		
Type	-	?	Density	$kg\ m^{-3}$	
Density	$kg\ m^{-3}$	910	cp	$J\ kg^{-1}\ K^{-1}$	
Yield Stress	Pa		Rgas	$J\ kg^{-1}\ K^{-1}$	296.798
Maximum Strain	-		Temperature	K	300.68
Young Modulus	Pa (10^6)	108	Remarks		
Poisson's Ratio	-	0.30			

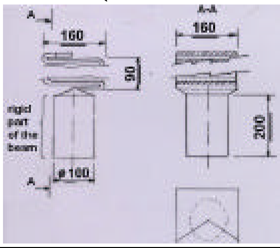
Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	?	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	300.68	lower end	clamped
Inflation Time	sec	?		
Remarks: Rigid cylinder mass: 75.7 g, radius 15mm, thickness 30mm				
			Remarks	

Environment		
Environmental Pressure	Pa	$1.03x10^5$
Gravity	$m\ s^{-2}$	10^{-4}
Temperature	K	293

Geometry					**2-2b**
Stowed Structure			**Deployed Structure: folded tube**		
Width	m		Diameter	m	$9.7x10^{-2}$
Total Length	m		Length	m	0.610
Thickness	m		Thickness	m	$1.52x10^{4}$
Volume	m^3		Volume	m^3	N/A
Sketch 			Sketch		
Properties					
Material: polyethylene			**Gas: air**		
Type	-	PET	Density	$kg\ m^{-3}$	
Density	$kg\ m^{-3}$	913	cp	$J\ kg^{-1}\ K^{-1}$	
Yield Stress	Pa		Rgas	$J\ kg^{-1}\ K^{-1}$	
Maximum Strain	-		Temperature	K	294.26
Young Modulus	Pa (10^6)	172	Remarks molecular weight: 28.97 kg/kmole		
Poisson's Ratio	-	0.25			
Loads and Boundary Conditions					
Loads			**Boundary Conditions**		
Pressure of Inflated Structure	Pa	16547	Geometrical Entity	Constraints	
Temperature Pressurized Gas	K	294.26	see drawing		
Inflation Time	sec	0.19			
Remarks: mass flow $4.54x10^{-2}$ x t kg/s					
			Remarks		
Environment					
Environmental Pressure	Pa	0			
Gravity	$m\ s^{-2}$	0			
Temperature	K	293			

Geometry						**2-2c**
Stowed Structure			**Deployed Structure**			
Width	m	0.160	Diameter	m	0.100	
Total Length	m	-	Length	m	3.005	
Thickness	m	510^{-5}	Thickness	m	-	
Volume	m^3	$\sim 1.610^{-3}$	Volume	m^3	0.024	

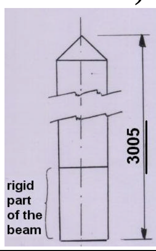
Sketch (dimensions in mm)



Total of 19 folds

Z

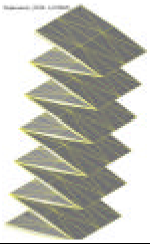
Sketch (dimensions in mm)

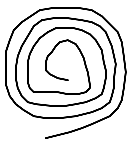


Properties					
Material: Polyamide			**Gas: N_2**		
Type	-	-	Density	kg m^{-3}	1250
Density	kg m^{-3}	1120	cp	J kg^{-1} K^{-1}	1040
Yield Stress	Pa (10^6)	90	Rgas	J kg^{-1} K^{-1}	297
Maximum Strain	-		Temperature	K	293
Young Modulus	Pa (10^6)	1500	Remarks		
Poisson's Ratio	-	0.3			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	5000	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	-	Rigid part	clamped
Inflation Time	sec	1.0		
Remarks Inflation through the rigid part				
			Remarks See "rigid part of the beam" in sketch	

Environment		
Environmental Pressure	Pa	1.013×10^5 / ~0
Gravity	m s^{-2}	-9.81 / ~0 / 9.81 (direction of z-axis)
Temperature	K	293

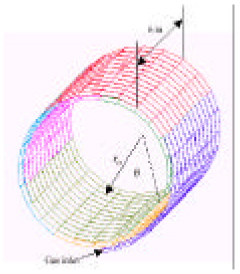
Geometry					**2-2d**
Stowed Structure			**Deployed Structure**		
Width	m	-	Diameter	m	0.150*
Total Length	m	3.000	Length	m	3.000
Thickness	m	$5x10^{-5}$	Thickness	m	$5x10^{-5}$
Volume	m^3	0.002	Volume	m^3	0.053
Sketch (Note: each fold has 0.25 length) 			Sketch * the section perimeter of the deployed structure is equal to the section perimeter of the stowed structure		
Properties					
Material: Mylar			**Gas: N_2**		
Type	-	92A	Density	kg m^{-3}	-
Density	kg m^{-3}	1390	cp	J kg^{-1} K^{-1}	1040
Yield Stress	Pa	-	Rgas	J kg^{-1} K^{-1}	297
Maximum Strain	-	-	Temperature	K	293
Young Modulus	Pa (10^6)	4900	Remarks		
Poisson's Ratio	-	0.3			
Loads and Boundary Conditions					
Loads			**Boundary Conditions**		
Pressure of Inflated Structure	Pa	-	Geometrical Entity	Constraints	
Temperature Pressurized Gas	K	-	Lower end	clamped	
Inflation Time	sec	1.0			
Remarks Mass inflow: $9.14x10^{-2}$Kg/s of Nitrogen Inflation through the lower end					
			Remarks rigid plane below structure		
Environment					
Environmental Pressure	Pa	$1.013x10^5$ / ~0			
Gravity	m s^{-2}	9.81 / ~0			
Temperature	K	293			

<table>
<tr><th colspan="1">Deployment of a rolled beam made of isotropic material</th><th>2-3</th></tr>
<tr><td colspan="2">Objectives</td></tr>
<tr><td colspan="2">Predict the deployment and the final shape of an inflated rolled beam.</td></tr>
<tr><td colspan="2">Particular issues</td></tr>
<tr><td colspan="2">Modelisation of thin shells and large displacement dynamic analysis.</td></tr>
<tr><td colspan="2">Input</td></tr>
<tr><td>Geometry, boundary conditions and loading
A rolled beam.
The beam is fixed at one end.
An internal pressure is applied to inflate the beam.
</td><td>Material properties

The tube is made of a polyamide film.</td></tr>
<tr><td colspan="2">Output</td></tr>
<tr><td colspan="2">deployment envelope (vs. time) and final shape.</td></tr>
<tr><td colspan="2">References</td></tr>
<tr><td>Analysis
1) Dynamics of Large Reflectors Dynamic Analysis Study for an Inflatable Space Rigidized Structure Type of Reflector (ESTEC final report 8455/89/NL/PM(SC))
2) Deployment Simulation of Ultra-Lightweight Inflatable Structures (JT Wang, AR Johnson, AIAA-2002-1261)</td><td>Testing
1) Dynamics of Large Reflectors Dynamic Analysis Study for an Inflatable Space Rigidized Structure Type of Reflector (ESTEC final report 8455/89/NL/PM(SC))</td></tr>
</table>

Geometry					**2-3a**
Stowed Structure			**Deployed Structure: rolled tube**		
Width	m		Diameter	m	$9.7x10^{-2}$
Total Length	m		Length	m	0.610
Thickness	m		Thickness	m	$1.52x10^{-4}$
Volume	m^3		Volume	m^3	N/A

Sketch



Sketch

Properties					
Material: polyethylene			**Gas: air**		
Type	-	PET	Density	$kg\ m^{-3}$	
Density	$kg\ m^{-3}$	913	cp	$J\ kg^{-1}\ K^{-1}$	
Yield Stress	Pa		Rgas	$J\ kg^{-1}\ K^{-1}$	
Maximum Strain	-		Temperature	K	294.26
Young Modulus	Pa (10^6)	172	Remarks molecular weight: 28.97 kg/kmole		
Poisson's Ratio	-	0.25			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	55158	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	294.26	inner end	2 corners clamped
Inflation Time	sec	0.35		
Remarks: mass flow $4.54x10^{-2}$ x t kg/s				
			Remarks	

Environment		
Environmental Pressure	Pa	0
Gravity	$m\ s^{-2}$	0
Temperature	K	293

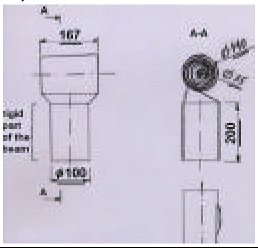
Geometry — 2-3b

Stowed Structure			Deployed Structure		
Width	m	0.167	Diameter	m	0.100
Total Length	m	-	Length	m	3.000
Thickness	m	$5x10^{-5}$	Thickness	m	-
Volume	m^3	$\sim 1.6x10^{-3}$	Volume	m^3	0.024

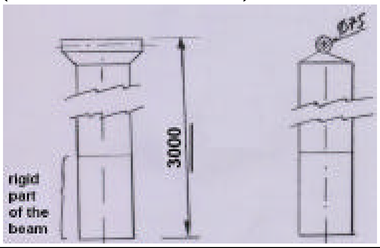
Sketch (dimensions in mm)

End cap diameter: 75 mm
End cap+folded structure diameter: 140mm

Z



Sketch (dimensions in mm)



Properties

Material: Polyamide			Gas: N_2		
Type	-	-	Density	kg m^{-3}	1250
Density	kg m^{-3}	1120	cp	J kg^{-1} K^{-1}	1040
Yield Stress	Pa (10^6)	90	Rgas	J kg^{-1} K^{-1}	297
Maximum Strain	-	-	Temperature	K	293
Young Modulus	Pa (10^6)	1500	Remarks		
Poisson's Ratio	-	0.3			

Loads and Boundary Conditions

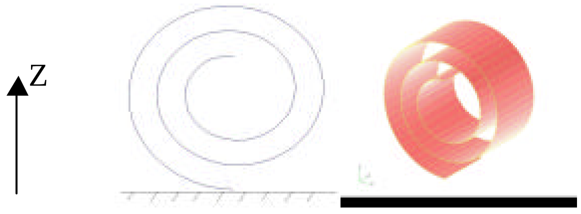
Loads			Boundary Conditions	
Pressure of Inflated Structure	Pa	5000	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	-	Rigid part	clamped
Inflation Time	sec	1.0		
Remarks Inflation through the rigid part				
			Remarks See "rigid part of the beam" in sketch	

Environment

Environmental Pressure	Pa	$1.013x10^5$ / ~0
Gravity	m s^{-2}	-9.81 / ~0 / 9.81 (direction of z-axis)
Temperature	K	293

Geometry					**2-3c**
Stowed Structure			**Deployed Structure**		
Width	m	-	Diameter	m	0.150*
Total Length	m	3.000	Length	m	3.000
Thickness	m	$5x10^{-5}$	Thickness	m	$5x10^{-5}$
Volume	m^3	0.002	Volume	m^3	0.053

Sketch (Note: structure makes a total angle of 5 π)



Sketch
* the section perimeter of the deployed structure is equal to the section perimeter of the stowed structure

Properties					
Material: Mylar			**Gas: N_2**		
Type	-	92A	Density	kg m^{-3}	-
Density	kg m^{-3}	1390	cp	J kg^{-1} K^{-1}	1040
Yield Stress	Pa	-	Rgas	J kg^{-1} K^{-1}	297
Maximum Strain	-	-	Temperature	K	293
Young Modulus	Pa (10^6)	4900	Remarks		
Poisson's Ratio	-	0.3			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	-	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	-	Outsider end	clamped
Inflation Time	sec	1.0		
Remarks Mass inflow: $9.14x10^{-2}$Kg/s of Nitrogen Inflation through the lower end				
			Remarks rigid plane below structure	

Environment		
Environmental Pressure	Pa	$1.013x10^5$ /~0
Gravity	m s^{-2}	-9.81 / ~0
Temperature	K	293

Deployment of a rolled torus made of isotropic material	**3-1**

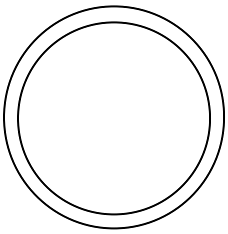
Objectives

Predict the deployment and the final shape of an inflated rolled torus.

Particular issues

Modelisation of thin shells and large displacement dynamic analysis.

Input

Geometry, boundary conditions and loading	**Material properties**
A rolled torus. The torus is fixed at one point. An internal pressure is applied to inflate the torus. 	The tube is made of a polyamide film.

Output

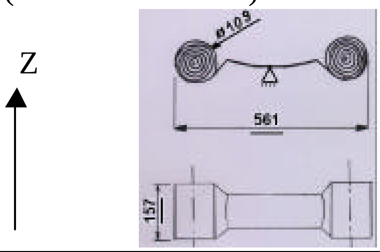
deployment envelope (vs. time) and final shape.

References

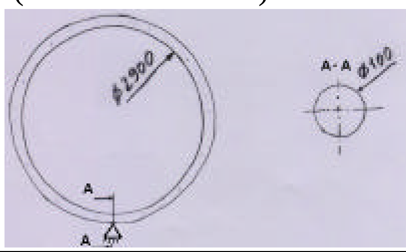
Analysis	**Testing**

Geometry						**3-1a**
Stowed Structure				**Deployed Structure**		
Width	m	0.157		Diameter	m	2.900
Total Length	m	-		Length	m	-
Thickness	m	$5x10^{-5}$		Thickness	m	-
Volume	m^3	~0		Volume	m^3	$7.3x10^{-2}$

Sketch (dimensions in mm)



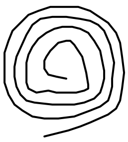
Sketch (dimensions in mm)



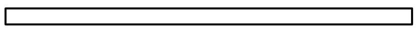
Properties					
Material: Polyamide			**Gas: N_2**		
Type	-	-	Density	$kg\ m^{-3}$	1250
Density	$kg\ m^{-3}$	1120	cp	$J\ kg^{-1}\ K^{-1}$	1040
Yield Stress	Pa (10^6)	90	Rgas	$J\ kg^{-1}\ K^{-1}$	297
Maximum Strain	-	-	Temperature	K	293
Young Modulus	Pa (10^6)	1500	Remarks		
Poisson's Ratio	-	0.3			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	5000	Geometrical Entity	Constraints
Temperature Pressurized Gas	K	-		
Inflation Time	sec	6.0		
Remarks Inflation through fixed point				
			Remarks See fixed point in sketch	

Environment		
Environmental Pressure	Pa	$1.013x10^5$ / ~0
Gravity	$m\ s^{-2}$	-9.81 / ~0 / 9.81 (direction of z-axis)
Temperature	K	293

<table>
<tr><th colspan="2">Controlled deployment of a rolled beam made of isotropic material</th><th>4-1</th></tr>
<tr><td colspan="3">Objectives</td></tr>
<tr><td colspan="3">Predict the deployment and the final shape of an inflated rolled beam including a control system for deployment.</td></tr>
<tr><td colspan="3">Particular issues</td></tr>
<tr><td colspan="3">Modelisation of control deployment.</td></tr>
<tr><td colspan="3">Input</td></tr>
<tr><td>Geometry, boundary conditions and loading
A rolled beam including a deployment control system.
The beam is fixed at one end.
An internal pressure is applied to inflate the beam.
</td><td colspan="2">Material properties

The tube is made of a polyamide film.</td></tr>
<tr><td colspan="3">Output</td></tr>
<tr><td colspan="3">deployment envelope (vs. time) and final shape.</td></tr>
<tr><td colspan="3">References</td></tr>
<tr><td>Analysis
1) Resistive Deployment of Inflatable Structures (M Salama, H Fang, M Lou, AIAA-2001-1339)</td><td colspan="2">Testing
1)</td></tr>
</table>

<table>
<tr><th colspan="2">Bending deflection of an isotropic pressurised beam</th><th>6-1</th></tr>
<tr><td colspan="3">Objectives</td></tr>
<tr><td colspan="3">Predict the deflection of an isotropic pressurised beam subjected to bending.</td></tr>
<tr><td colspan="3">Particular issues</td></tr>
<tr><td colspan="3">Modelisation of thin shells.</td></tr>
<tr><td colspan="3">Input</td></tr>
<tr><td>Geometry, boundary conditions and loading
A straight beam.
The beam is fixed at one end.
An internal pressure is applied to the beam and a load is applied at the free end.
</td><td colspan="2">Material properties
The tube is made of a polyimide film.</td></tr>
<tr><td colspan="3">Output</td></tr>
<tr><td colspan="3">deflection of the free end.</td></tr>
<tr><td colspan="3">References</td></tr>
<tr><td>Analysis
1) Geometric Scaling Properties Of Inflatable Structures For Use In Space Solar Power Generation (D Holland, L Virgin, M Tinker, K Slade, AIAA-2002-1264)</td><td colspan="2">Testing
1) Geometric Scaling Properties Of Inflatable Structures For Use In Space Solar Power Generation (D Holland, L Virgin, M Tinker, K Slade, AIAA-2002-1264)</td></tr>
</table>

Geometry					**6-1a**
Stowed Structure			**Deployed Structure: beam**		
Width	m		Diameter	m	0.152
Total Length	m		Length	m	2.44
Thickness	m		Thickness	m	$5.08x10^5$
Volume	m^3		Volume	m^3	?
Sketch			Sketch		

Properties					
Material: Kapton-HN			**Gas: air**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1420	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	2492	Remarks		
Poisson's Ratio	-	0.34			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	3447	Geometrical Entity	Constraints
Upper end lateral load	N	2.7	lower end	fixed
Remarks: polystyrene end plugs thickness $1.9x10^{-2}$m, Young's modulus 3200 N/mm^2, Poisson's ratio 0.25, density 29.9 kg/m^3.				
			Remarks	

Environment		
Environmental Pressure	Pa	$1.013x10^5$
Gravity	m s^{-2}	9.81
Temperature	K	293

Buckling load of an isotropic pressurised beam	**6-2**

Objectives

Predict the buckling load of an isotropic pressurised beam subjected to an axial compressive load.

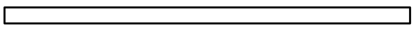
Particular issues

Modelisation of thin shells.

Input

Geometry, boundary conditions and loading

A straight beam.
The beam is fixed at one end.
An internal pressure is applied to the beam and a compressive load is applied at the free end.



Material properties

The tube is made of a polyimide film.

Output

buckling load of the beam.

References

Analysis

1) Geometric Scaling Properties Of Inflatable Structures For Use In Space Solar Power Generation (D Holland, L Virgin, M Tinker, K Slade, AIAA-2002-1264)

Testing

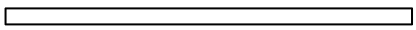
1) Geometric Scaling Properties Of Inflatable Structures For Use In Space Solar Power Generation (D Holland, L Virgin, M Tinker, K Slade, AIAA-2002-1264)

Geometry					**6-2a**
Stowed Structure			**Deployed Structure: beam**		
Width	m		Diameter	m	8.89×10^{-2}
Total Length	m		Length	m	0.889
Thickness	m		Thickness	m	5.08×10^{-5}
Volume	m^3		Volume	m^3	?
Sketch			Sketch 		

Properties					
Material: Kapton-HN			**Gas: air**		
Type	-	PI	Density	$kg\ m^{-3}$	
Density	$kg\ m^{-3}$	1420	cp	$J\ kg^{-1}\ K^{-1}$	
Yield Stress	Pa		Rgas	$J\ kg^{-1}\ K^{-1}$	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	2492	Remarks		
Poisson's Ratio	-	0.34			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	6895	Geometrical Entity	Constraints
Upper end axial load	N	buckl.	lower end	fixed
Remarks: polystyrene end plugs thickness 1.9×10^{-2}m, Young's modulus 3200 N/mm^2, Poisson's ratio 0.25, density 29.9 kg/m^3.				
			Remarks	

Environment		
Environmental Pressure	Pa	1.013×10^5
Gravity	$m\ s^{-2}$	9.81
Temperature	K	293

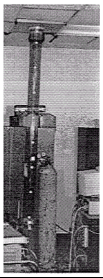
<table>
<tr><th colspan="1">Dynamic Analysis of an isotropic pressurised beam</th><th>6-3</th></tr>
<tr><td colspan="2">Objectives</td></tr>
<tr><td colspan="2">Predict the eigenvalues and mode shapes of an isotropic pressurised beam.</td></tr>
<tr><td colspan="2">Particular issues</td></tr>
<tr><td colspan="2">Modelisation of thin shells.</td></tr>
<tr><td colspan="2">Input</td></tr>
<tr><td>Geometry, boundary conditions and loading
A straight beam.
The beam is free-free or fixed at one end (cantilever).
An internal pressure is applied to the beam.
</td><td>Material properties
The tube is made of a polyimide film.</td></tr>
<tr><td colspan="2">Output</td></tr>
<tr><td colspan="2">eigenvalues and mode shapes of the beam.</td></tr>
<tr><td colspan="2">References</td></tr>
<tr><td>Analysis
1) Investigation of Nonlinear Pressurization and Modal Restart in MSC/NASTRAN for Modeling Thin Film Inflatable Structures (K Smalley, M Tinker, R Fischer, AIAA-2001-1409)
2) Mode Splitting in an Inflated Polyimide Cylinder with Circumferential Asymmetry (K Slade, L Virgin, M Tinker, AIAA-2001-1411)</td><td>Testing
1) Investigation of Nonlinear Pressurization and Modal Restart in MSC/NASTRAN for Modeling Thin Film Inflatable Structures (K Smalley, M Tinker, R Fischer, AIAA-2001-1409)
2) Mode Splitting in an Inflated Polyimide Cylinder with Circumferential Asymmetry (K Slade, L Virgin, M Tinker, AIAA-2001-1411)</td></tr>
</table>

Geometry					**6-3a**
Stowed Structure			**Deployed Structure: beam**		
Width	m		Diameter	m	0.152
Total Length	m		Length	m	2.44
Thickness	m		Thickness	m	$5.08x10^{-5}$
Volume	m^3		Volume	m^3	?
Sketch			Sketch		

Properties					
Material: Kapton			**Gas: air**		
Type	-	PI	Density	$kg\ m^{-3}$	
Density	$kg\ m^{-3}$	1500	cp	$J\ kg^{-1}\ K^{-1}$	
Yield Stress	Pa		Rgas	$J\ kg^{-1}\ K^{-1}$	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	3530	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	9653	Geometrical Entity	Constraints
			free-free	
Remarks: styrofoam end plugs beams are formed by bonding the Kapton layer using a $2.54x10^{-4}$m thick epoxy adhesive				
			Remarks	

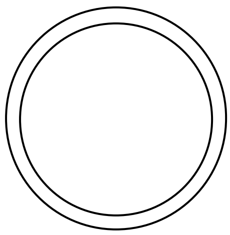
Environment		
Environmental Pressure	Pa	0
Gravity	$m\ s^{-2}$	0
Temperature	K	293

Geometry					**6-3b**
Stowed Structure			**Deployed Structure: beam**		
Width	m		Diameter	m	0.152
Total Length	m		Length	m	2.44
Thickness	m		Thickness	m	$5.08x10^{-5}$
Volume	m^3		Volume	m^3	?
Sketch			Sketch 		

Properties					
Material: Kapton			**Gas: air**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1500	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	3530	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	3447	Geometrical Entity	Constraints
			lower end	clamped
Remarks: styrofoam end plugs beams are formed by bonding the Kapton layer using a $2.54x10^{-4}$m thick epoxy adhesive				
			Remarks	

Environment		
Environmental Pressure	Pa	$1.013x10^5$
Gravity	m s^{-2}	9.81
Temperature	K	293

<table>
<tr><th>Dynamic Analysis of an isotropic pressurised torus</th><th>7-1</th></tr>
<tr><td colspan="2">Objectives</td></tr>
<tr><td colspan="2">Predict the eigenvalues and mode shapes of an isotropic pressurised torus.</td></tr>
<tr><td colspan="2">Particular issues</td></tr>
<tr><td colspan="2">Modelisation of thin shells.</td></tr>
<tr><td colspan="2">Input</td></tr>
<tr><td>Geometry, boundary conditions and loading
A cylindrical torus.
The torus is in free-free conditions.
An internal pressure is applied to the torus.
</td><td>Material properties

The torus is made of a polyimide film.</td></tr>
<tr><td colspan="2">Output</td></tr>
<tr><td colspan="2">eigenvalues and mode shapes of the torus.</td></tr>
<tr><td colspan="2">References</td></tr>
<tr><td>Analysis
1) Dynamic Characterization of an inflatable Concentrator for Solar Thermal Propulsion (L Leigh, H, Hamidzadeh, M Tinker, K Slade, AIAA-2001-1406)
2) Vibration Analysis and Control of an Inflatable Toroidal Satellite Component using Piezoelectric Actuators and Sensors (A Jha, PhD dissertation)</td><td>Testing
1) Dynamic Characterization of an inflatable Concentrator for Solar Thermal Propulsion (L Leigh, H, Hamidzadeh, M Tinker, K Slade, AIAA-2001-1406)
2) Experimental Modal Analysis and Damping Estimation for an Inflated Thin-Film Torus (D Griffith, J. Main, Journal of Guidance, Control, and Dynamics, Vol. 25, No 4)</td></tr>
</table>

Geometry						**7-1a**
Stowed Structure			**Deployed Structure: torus**			
Width	m		Cross-section diameter	m	0.152	
Total Length	m		Outside overall diameter	m	1.83	
Thickness	m		Thickness	m	5.08×10^{-5}	
Volume	m^3		Volume	m^3	?	
Sketch			Sketch			

Properties					
Material: Kapton 300-JP			**Gas: air**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1500	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	2760	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	3447	Geometrical Entity	Constraints
			free-free	
Remarks				
			Remarks	

Environment		
Environmental Pressure	Pa	0
Gravity	m s^{-2}	0
Temperature	K	293

Geometry	**7-1b**

Stowed Structure			**Deployed Structure: torus**		
Width	m		Cross-section diameter	m	2.44
Total Length	m		Main diameter	m	15.24
Thickness	m		Thickness	m	7.62×10^{-5}
Volume	m^3		Volume	m^3	?
Sketch			Sketch		

Properties					
Material: Kapton			**Gas: air**		
Type	-	PI	Density	$kg\ m^{-3}$	
Density	$kg\ m^{-3}$	1418	cp	$J\ kg^{-1}\ K^{-1}$	
Yield Stress	Pa		Rgas	$J\ kg^{-1}\ K^{-1}$	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	2550	Remarks		
Poisson's Ratio	-	0.34			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	3447	Geometrical Entity	Constraints
			free- free	
Remarks				
			Remarks	

Environment		
Environmental Pressure	Pa	0
Gravity	$m\ s^{-2}$	0
Temperature	K	293

Geometry					**7-1c**
Stowed Structure			**Deployed Structure: torus**		
Width	m		Cross-section diameter	m	0.15
Total Length	m		Main diameter	m	1.98
Thickness	m		Thickness	m	4.6×10^{-5}
Volume	m^3		Volume	m^3	?
Sketch			Sketch		

Properties					
Material: Kapton-HN			**Gas: air**		
Type	-	PI	Density	$kg\ m^{-3}$	
Density	$kg\ m^{-3}$	1420	cp	$J\ kg^{-1}\ K^{-1}$	
Yield Stress	Pa		Rgas	$J\ kg^{-1}\ K^{-1}$	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	2500	Remarks		
Poisson's Ratio	-	0.34			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Pressure of Inflated Structure	Pa	5520	Geometrical Entity	Constraints
			free-free	
Remarks: Torus panels thermally formed from flat sheets. Joining region 5.1×10^{-2}m wide and 3.6×10^{-4} to 1.5×10^{-4}m thick (from inner to outer).				
			Remarks	

Environment		
Environmental Pressure	Pa	0
Gravity	$m\ s^{-2}$	0
Temperature	K	293

Wrinkling of an isotropic rectangular membrane subjected to edge shear loading	**8-1**

Objectives

Predict the wrinkling pattern and the wrinkles amplitude of a thin membrane subjected to edge shear loading.

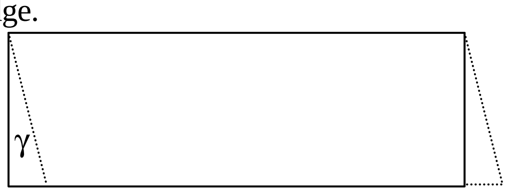
Particular issues

Modelisation of thin membranes.

Input

Geometry, boundary conditions and loading

A rectangular plane membrane.
One of the long edge is fixed (blocked translations and rotations).
A shear load is applied on the other long edge.



Material properties

The membrane is made of polyimide film.

Output

Wrinkling pattern (angle and wavelength)
Wrinkling amplitude A

References

Analysis

1) Computation of wrinkles amplitudes in thin membranes (YW Wong, S Pellegrino, AIAA-2002-1369)

Testing

1) Computation of wrinkles amplitudes in thin membranes (YW Wong, S Pellegrino, AIAA-2002-1369)

Geometry						**8-1a**
Stowed Structure			**Deployed Structure: membrane**			
Width	m		Height	m	0.128	
Total Length	m		Length	m	0.380	
Thickness	m		Thickness	m	$2.5x10^{-5}$	
Volume	m^3		Volume	m^3	?	
Sketch			Sketch			

Properties					
Material: Kapton			**Gas:**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1500	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	3530	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
Prescribed displacement	mm	3	Geometrical Entity	Constraints
			long edge	clamped
Remarks:				
			Remarks	

Environment		
Environmental Pressure	Pa	10^5
Gravity	m s^{-2}	9.81
Temperature	K	293

Wrinkling of an isotropic rectangular membrane subjected to point shear loading — 8-2

Objectives

Predict the wrinkling pattern and the wrinkles amplitude of a thin membrane subjected to point shear loading.

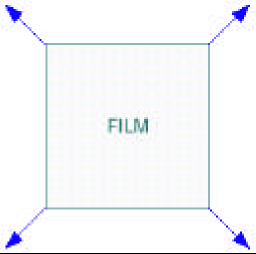
Particular issues

Modelisation of thin membranes.

Input

Geometry, boundary conditions and loading

A square plane membrane.
The membrane is fixed at the corners.
A point loading is applied to 1 to 4 corners.



Material properties

The membrane is made of polyimide film.

Output

Wrinkling pattern (angle and wavelength)
Wrinkling amplitude A

References

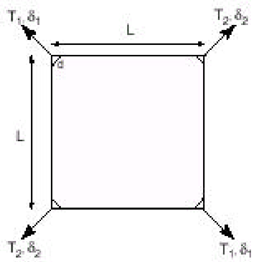
Analysis

1) Prediction of wrinkle amplitudes in square solar sail (YW Wong, S Pellegrino, AIAA-2003-1982)
2) A two variables parameter membrane model for wrinkling analysis of membrane structures (H Ding, B Yang, M Lou, H Fang, AIAA-2002-1460)

Testing

1) Prediction of wrinkle amplitudes in square solar sail (YW Wong, S Pellegrino, AIAA-2003-1982)
2) Comparing photogrammetry with a conventional displacement measurement technique on a 0.5m square Kapton membrane (UK Dharamsi, JR Blandino, AIAA-2002-1258)

Geometry						**8-2a**
Stowed Structure			**Deployed Structure: membrane**			
Width	m		Height	m	0.5	
Total Length	m		Length	m	0.5	
Thickness	m		Thickness	m	$2.5x10^{-5}$	
Volume	m^3		Volume	m^3	?	
Sketch			Sketch 25mm chamfer reinforced with 25mm x 20mm Kapton of 0.1mm thickness			

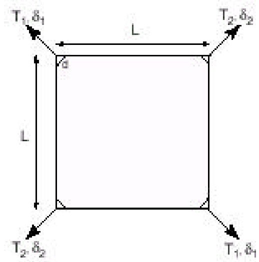


Properties					
Material: Kapton			**Gas:**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1500	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	3530	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
loading at four corners	N	5	Geometrical Entity	Constraints
			isostatic	
Remarks: 25mm chamfer reinforced with 25mm x 20mm Kapton of 0.1mm thickness				
			Remarks	

Environment		
Environmental Pressure	Pa	0
Gravity	m s^{-2}	0
Temperature	K	293

Geometry					**8-2b**
Stowed Structure			**Deployed Structure: membrane**		
Width	m		Height	m	0.5
Total Length	m		Length	m	0.5
Thickness	m		Thickness	m	$2.5x10^{-5}$
Volume	m^3		Volume	m^3	?
Sketch			Sketch		

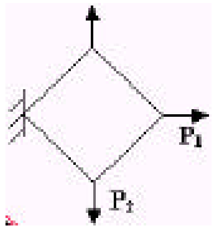


Properties					
Material: Kapton			**Gas:**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1500	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	3530	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
loading at two corners T1	N	20	Geometrical Entity	Constraints
loading at two corners T2	N	5	isostatic	
Remarks: 25mm chamfer reinforced with 25mm x 20mm Kapton of 0.1mm thickness				
			Remarks	

Environment		
Environmental Pressure	Pa	0
Gravity	m s^{-2}	0
Temperature	K	293

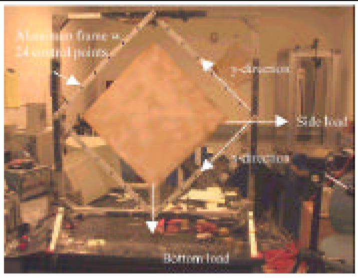
Geometry					**8-2c**
Stowed Structure			**Deployed Structure: membrane**		
Width	m		Height	m	0.8
Total Length	m		Length	m	0.8
Thickness	m		Thickness	m	$7.62\text{x}10^{-5}$
Volume	m^3		Volume	m^3	?
Sketch			Sketch		



Properties					
Material: Kapton			**Gas:**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1500	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	3530	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
right corner	N	13.3	Geometrical Entity	Constraints
upper and lower corners	N	17.8	left corner	fixed
Remarks: corners of the square are reinforced with 0.397mm thick aluminium (E=69000 MPa, ν=0.3, ρ=2700 kg/m^3) plates on both sides. Dimensions of each plate are 39mm x 35mm and by 55mm.				
			Remarks	

Environment		
Environmental Pressure	Pa	0
Gravity	m s^{-2}	0
Temperature	K	293

Geometry					**8-2d**
Stowed Structure			**Deployed Structure: membrane**		
Width	m		Height	m	0.5
Total Length	m		Length	m	0.5
Thickness	m		Thickness	m	2.5×10^{-6}
Volume	m^3		Volume	m^3	?
Sketch			Sketch 		

Properties					
Material: Kapton			**Gas: air**		
Type	-	PI	Density	kg m^{-3}	
Density	kg m^{-3}	1500	cp	J kg^{-1} K^{-1}	
Yield Stress	Pa		Rgas	J kg^{-1} K^{-1}	
Maximum Strain	-		Temperature	K	
Young Modulus	Pa (10^6)	3530	Remarks		
Poisson's Ratio	-	0.30			

Loads and Boundary Conditions				
Loads			**Boundary Conditions**	
lower and right corner	N	2.45	Geometrical Entity	Constraints
			upper and left corners	fixed
Remarks: 10^{-3}mm vapor deposited aluminium coating.				
			Remarks	

Environment		
Environmental Pressure	Pa	10^5
Gravity	m s^{-2}	9.81
Temperature	K	293