Nonlinear Analysis Of An EPDM Hydraulic Accumulator Bladder

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Agenda

Race-Tec Overview
Accumulator Experimental Testing
Material Testing
Numerical Analysis:
  1. Linear Buckling
  2. Post Buckling using Constrained Methods
  3. Post Buckling using Artificial Damping
Conclusion
Overview: Testing at Race-Tec

Material Testing Machines

- Radial load
- CCD Spectrometer
- Micro Hardness & Microscope
- CMM Inspection
- Hardness
- Tension & Compression
Overview: What Are Accumulators?

- A 3D nonlinear FE simulation of an Ethylene-Propylene-Diene Monomer (EPDM) hydro-pneumatic accumulator bladder at 3:1 compression ratio will be presented.
- Accumulators are used as part of a hydraulic system so that:
  - The pump size can be reduced and retain ability to cope with extremes of demand.
  - The supply circuit can respond more quickly to sudden demands.
  - The system pressure fluctuations are smoothed.
Overview: What Are Accumulators?

- A polymer bladder divides the accumulator into two cavities:
  1. One connected to an open hydraulic system
  2. The other a closed volume containing nitrogen
- Accumulator retention bead is compressed
- Initial pre charge pressure is applied to the nitrogen cavity
- Subsequent hydraulic system pressure causes significant deformation and collapse of the bladder
Overview: Why Accumulator Simulations?

• **Ensure that buckling (whether 4-5-6 lobes) does not occur in the working zone between Max/Min system pressure**
  - The trilobe collapse with an “acorn” shaped bladder (as in this presentation) will always occur so cannot be limited to a great extent
  - The buckling load and shape is interesting in this case from a numerical validation point of view
• **The prediction of strain is a key issue in all accumulator geometries**
  - For “acorn” accumulators having a horizontal split line when mounted on its side, a strain concentration can significantly influence the design strength
  - Accumulators can invert with a multipoint “petal” buckle, and then fail circumferentially along a mould split line if a peak petal deformation coincides at this point
• **The ability to provide a high compression ratio without failure is essential to the design**
Overview: What Are We Looking At?

- Numerical results are compared to physical test results for:
  - The buckling mode
  - The buckling pressure factor
  - Post buckling behaviour
- In addition, the numerical maximum strain levels are compared with known material limits
Product & Material Testing
Product Testing

- Specially developed transparent case
- Vacuum gradually applied to the accumulator (Maximum 0.0025 MPa)
  - Vacuum pump attached to left hand side
  - Pressure transducer attached downstream
- Pressure at initial buckling measured as 0.0022 MPa
- The numerical analysis will apply the pressure difference as a vacuum to the accumulator
Material Testing

- $\nu \leq 0.5$ with a linear isotropic material model is not acceptable for large strain analysis.
- Need a hyperelastic material model, based on strain energy formulations (e.g. Mooney, Ogden, etc.).
- To obtain material coefficients necessary, the following experimental data is required:
  1. Tensile Test
     - Constant uniaxial stress state in specimen
  2. Compression
     - Constant biaxial stress state in specimen

\[
\sigma_{ij} = C_{ijkl}\varepsilon_{kl}
\]

\[
W_{\text{deviatoric}}^{mr} = C_{10}(\hat{I}_1 - 3) + C_{01}(\hat{I}_2 - 3)
\]
Material Testing

• Test Results EPDM 70

[Diagram showing stress-strain curve for Tension and Compression, with 'Smoothed across origin' noted on the graph]
Material Testing

- Interactive Experimental Data Curve Fitting used
- Provide a stable and accurate set of hyperelastic material coefficients
- Best fit obtained using 3 terms for the Ogden strain energy function
- Small strain fit crucial for correct buckling behaviour
- Both tensile-only and the full tensile-compression data were used to obtain consistent coefficients over the strain range of the test
Numerical Analysis:
General Features Used
Numerical Analysis: Cavity Definition

- Cavity defined from a continuous set of element faces
  - Mostly from the accumulator, but closed by special cavity elements
  - Volume automatically calculated
  - Open or Closed cavities possible – **Open** in this case
- Application of gas pressure could also been carried out directly – but P-V characteristics would not be available
- Pressure updated incrementally within the cavity:
  \[ P = P_0 + \Delta P \]
- The density is then updated:
  \[ M = \rho V \]
Marc automatically handles the changing contact conditions (incl. self contact, separation, sliding and friction)

- A bilinear friction model is used
  - Based on an elastoplastic concept
  - Provides an accurate model in the presence of large relative deformations and friction coefficients in excess of 1.5
  - Friction between EPDM and the external cavity ~0.5
  - Friction between EPDM ~0.8
Numerical Analysis:
Linear Buckling
Numerical Analysis: Linear Buckling

- Linear (eigenvalue) buckling analysis initially performed
- Internal pressure applied as a preload
- First mode predicted as a trilobe, at 0.0025 MPa (RT test 0.0022 MPa)
- 14% difference
- Analysis time ≈ few minutes

- The shape agrees with general observation:
  - If the outer diameter of the cavity is smaller than its length a trilobe collapse is found
  - If the outer diameter is ~1.5 times its length, then a penta-lobe is found
Numerical Analysis:
Arc-Length
Numerical Analysis: Arc-Length

• Commonly known as “arc-length” methods
• Four analysis steps:
  1. Installation
  2. Initial gas preload
  3. Eigenvalue buckling solution
     • Including geometric and material nonlinearity
     • Mesh automatically modified (perturbed) according to:
       \[ \delta_{\text{new}} = \delta_{\text{last}} + \text{factor} \times \delta_{\text{buckle}} \]
     • \( \delta_{\text{buckle}} \) is based on mode one deformed shape in this case
  4. Arc length solution using Advanced Crisfield method (Falzon method to determine roots)
Numerical Analysis: Post Buckling Control

- Automatic limits imposed on the magnitude of iterative displacement ($\delta u$)
- Effective way to control “runaway” displacements during the iterative procedure
- Particularly useful for initially “loose” assemblies and for buckling analyses involving sudden and large deformation
- Used in all subsequent analyses shown
Numerical Analysis: Arc-Length

- Initial buckling pressure 0.0021 MPa (RT test 0.0022 MPa)
- 5% difference
Numerical Analysis: Quasi-Static Damping
Numerical Analysis: Newton-Raphson Solution

- Marc uses artificial numerical damping with standard Newton-Raphson iterations to “skip” post-buckling softening behaviour
  - Useful in static analyses when arc-length-type methods are too expensive or unforeseen
- When the load step becomes smaller than the user-defined minimum value, a factored lumped mass matrix is added to the stiffness matrix
- If the load step becomes larger than the minimum, option is switched off automatically
- For example:

![Diagram showing initial buckling, post-buckling stiffening, and softening jump](image)
Numerical Analysis: Newton-Raphson Solution

- Two analyses performed using automatic load incrementation (MultiCriteria)
  1. With a perturbation (as previous arc-length method)
     - Initial buckling pressure 0.00265 MPa (RT test 0.0022MPa)
     - 20% difference
  2. Without a perturbation
     - Initial buckling pressure 0.00282MPa (RT test 0.0022MPa)
     - 28% difference
  - Post-buckling stiffness also compares well

P-V response:
Numerical Analysis: Result Comparison
Numerical Analysis: Results Comparison

- P-V response for all analyses
- Post-buckling response correlates well:
  - Initially bending into trilobe shape
  - Subsequent compression and twist with contact

![Graph showing P-V response with a 3:1 compression ratio limit.](image)
Numerical Analysis: Results Comparison

- Close-up view around initial buckling point
- Good correlation in the responses between the different numerical solutions used
- Response shows a good correlation with test for the Initial buckling load
- Estimated buckling load range: 0.0021 – 0.0028 MPa
- With accurate material testing, very close correlation can be achieved with large strain buckling of elastomers
- Arc-Length produced closest correlation, as would be expected
- Linear buckling correlation is more of a happy coincidence...
Numerical Analysis: Results Comparison

Deformation Response from Test

Initial Buckling

Intermediate

Max. Pressure
Deformation Response of each Analysis

Arc-Length

No Perturbation

Perturbation
Numerical Analysis: Results Comparison

Deformation comparison with test
• Maximum pressure applied (0.0025MPa)
• Twist is consistent
• Bottom of accumulator is flatter – perhaps an effect of friction or moulding irregularities
• Peak equivalent strain response ~33%
• EPDM @25°C has breaking strain of 375-400%
• Viton @25°C has breaking strain of 250-300%
• Key value if the part needs a mould split line
Conclusion

- Consistent buckling and post buckling behaviour predicted from all analysis methods used
- Ability to predict with some degree of confidence:
  - Initial buckling pressure
  - Deformation
  - Ability of accumulator to handle the design pressure ratio
- Maximum strain information enables the reduction of failure mechanisms from early designs
- MSC.Marc provides a robust application for predicting geometrically and materially nonlinear buckling behaviour of elastomers
- Accurate material data is essential