HYDRAULIC CYLINDER LOAD CAPACITY

VIC 26-27 May 2008
WP 2 DESIGN BY ANALYSIS

• T2.1 STRUCTURAL ANALYSIS

Objectives: Buckling theoretical model of H.C for several boundary conditions

WP 6 TESTING AND MONITORING PROCEDURES

• T6.1.1 FIELD TESTING
• T6.1.2 LAB TESTING

Objectives: Experimental lab buckling of H.C for several boundary conditions
(Bench Tests)
Field buckling tests of H.C using real machines: Farm loader and back-hoe
Indoor buckling tests of H.C using a real mini back-hoe machine
WORK PERFORMED DURING THE LAST PERIOD (37-48 months)

1. Bench tubular rods experimental buckling tests.

2. Bench experimental buckling tests with hydraulic cylinder with tubular rods.

3. Bench experimental tests with hydraulic cylinder rods in order to evaluate the material resistance properties (Bending and Tensile Tests).

4. Visual Basic software for the mathematical model evaluation.

5. Experimental tests with tubular rods filled with ceramic material (collaboration with BCE).


7. Field Tests: (Collaboration with HIDRAR)
   - Indoor test with backhoe (HIDRAR/UPC) (cylinders and rods)
   - Field test with backhoe (HIDRAR-BMH)
<table>
<thead>
<tr>
<th></th>
<th>year</th>
<th>EXP</th>
<th>Initial Imperfection</th>
<th>Friction Torques</th>
<th>Load Eccentricity</th>
<th>Actuator Weight</th>
<th>Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoblit, Fred.</td>
<td>1950</td>
<td></td>
<td>is considered</td>
<td></td>
<td></td>
<td></td>
<td>is considered</td>
</tr>
<tr>
<td>K.L Seshasai</td>
<td>1975</td>
<td></td>
<td>as initial data</td>
<td></td>
<td></td>
<td></td>
<td>is considered (Hoblit)</td>
</tr>
<tr>
<td>Bennett, M.C</td>
<td>1978</td>
<td></td>
<td>as initial data</td>
<td>only for piston rod articulation</td>
<td></td>
<td></td>
<td>reaction in piston rod articulation</td>
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<tr>
<td>Ravishankar, N.</td>
<td>1980</td>
<td></td>
<td>elastic rigidity in connection point</td>
<td></td>
<td></td>
<td></td>
<td>as a distributed load</td>
</tr>
<tr>
<td>Chai Hong Yoo</td>
<td>1986</td>
<td></td>
<td>through FEM</td>
<td>through FEM</td>
<td>through FEM</td>
<td>through FEM</td>
<td></td>
</tr>
<tr>
<td>S. Baragetti</td>
<td>2001</td>
<td></td>
<td>initial definition as sinusoidal</td>
<td>Equivalents for both sides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Norma ISO/TS 13725</td>
<td>2001</td>
<td></td>
<td>is considered</td>
<td>is considered</td>
<td>is considered</td>
<td>is considered (Hoblit)</td>
<td></td>
</tr>
<tr>
<td>Yishou T., Wenwei, W.</td>
<td>2004</td>
<td></td>
<td>is considered</td>
<td>distributed load in tube and</td>
<td></td>
<td></td>
<td>is considered (Hoblit)</td>
</tr>
</tbody>
</table>
Important parameters have been considered to achieve a better knowledge about H.C BUCKLING PHENOMENA:

1- Misalignment: rod / cylinder tube
   • Clearance between gland and rod
   • Cylinder body deformation due to oil pressure (CIMNE)
   • Guide ring wear effect (TRELLEBORG SS)

2- Interaction in pin/bushing joint (Friction)
   • Friction torques in hydraulic cylinder end joints

3- Mechanism layout effect on load capacity
THEORETICAL MODEL MATRIX

\begin{equation}
\begin{bmatrix}
\sin(k_1 L_1) & 0 & 0 & -1 & 0 & \frac{L_2}{PL} \cos(k_1 L_1) & \frac{L_1}{PL} \\
0 & \cos(k_2 L) & \sin(k_2 L) & 0 & 0 & 0 & \frac{1}{P} \\
0 & \cos(k_2 L_1) & \sin(k_2 L_1) & -1 & 0 & \frac{L_2}{PL} & \frac{L_1}{PL} \\
-k_1 \cos(k_1 L) & -k_2 \sin(k_2 L_1) & k_2 \cos(k_2 L_1) & 0 & -1 & -\frac{k_1 \sin(k_1 L_1)}{P} & 0 \\
0 & 0 & 0 & K_c P & 0 & -K_c & -K_c \\
k_1 & 0 & 0 & 0 & 0 & -\frac{1}{PL} & \frac{1}{PL} \\
0 & -k_2 \sin(k_2 L) & k_2 \cos(k_2 L) & 0 & 0 & -\frac{1}{PL} & \frac{1}{PL}
\end{bmatrix}
\end{equation}
Actuator as a component of the mechanism

M23 is ACTIVE TORQUE

1st Case
\( \omega_2 > \omega_3 > 0 \)

ANG. VELOCITY of rod is positive and
TORQUE in rod pin is positive

ROD TORQUE POWER IS POSITIVE

M23 is RESISTIVE TORQUE

2nd Case
\( \omega_3 > \omega_2 > 0 \)

ANG. VELOCITY of rod is positive and
TORQUE in rod pin is negative

ROD TORQUE POWER IS NEGATIVE
Experiments with hydraulic cylinders

Previous Experimental work

ROD DIAMETER: 30mm
GLAND DIAMETER:
30, 30,2, 30,4, 30,6
Pin diameter = 22mm and bush diameter = 25,6 mm

Theoretical Model vs Experimental Results (frictionless)

Experimental results (frictionless)

Theoretical model (frictionless)

<table>
<thead>
<tr>
<th>Gland mm</th>
<th>30</th>
<th>30,2</th>
<th>30,4</th>
<th>30,6</th>
<th>31</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Misalig. Angle (°)</td>
<td>0,136</td>
<td>0,198</td>
<td>0,275</td>
<td>0,341</td>
<td>0,473</td>
<td>0,802</td>
</tr>
</tbody>
</table>
FRICTION and FRICTIONLESS JOINTS COMPARISON

<table>
<thead>
<tr>
<th>Gland Diameter (mm)</th>
<th>$\Theta_1$ (grades)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0,136</td>
</tr>
<tr>
<td>30,2</td>
<td>0,198</td>
</tr>
<tr>
<td>30,4</td>
<td>0,275</td>
</tr>
<tr>
<td>30,6</td>
<td>0,341</td>
</tr>
<tr>
<td>31</td>
<td>0,473</td>
</tr>
<tr>
<td>32</td>
<td>0,802</td>
</tr>
</tbody>
</table>
Strain gauges for bending moment measurement along the rod.
Bending torques measured through strain gauges

BENDING MOMENT DISTRIBUTION
along ROD for several LOADS

Position (rod side) X (mm)

Bending moment (N m)

100 bar
200
300
400
500
600
700
750
770

567 mm
Lado 2
225
225
30
Lado 1

Image of a rod with labels 1, 2, 3.
REAL BI-ARTICULATED CYLINDERS

DUMPER TRUCK
<table>
<thead>
<tr>
<th>Mechanisms (examples)</th>
<th>Real behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>bi-articulated</td>
<td>bi-articulated</td>
</tr>
<tr>
<td>Clamped-articulated with torques</td>
<td>Clamped-articulated with torques</td>
</tr>
<tr>
<td>bi-articulated with torques of different sense</td>
<td>bi-articulated with torques of different sense</td>
</tr>
<tr>
<td>Bi-articulated with torques of same sense</td>
<td>Bi-articulated with torques of same sense</td>
</tr>
</tbody>
</table>
Bench experimental tests with hydraulic cylinder rods in order to evaluate the material resistance properties (Bending and Tensile Tests)
TUBE ROD
H.Tubes St 37
30X20 and 30X24mm
L= 500mm
BENDING STRESS DETERMINATION

(TUBE AND BAR ROD BENDING TESTS)

BAR ROD

Rod F-114
30mm diameter
L = 500mm
EXPERIMENTAL BENDING RESULTS WITH BAR RODS
(30mm diameter and L=500mm)

<table>
<thead>
<tr>
<th>Test Nº</th>
<th>Machine (Limit force) (kN)</th>
<th>Max. load (Elastic Zone) (kN)</th>
<th>Equivalent Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>15</td>
<td>707</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>14</td>
<td>660</td>
</tr>
</tbody>
</table>

Average: 684MPa
<table>
<thead>
<tr>
<th>Tube Nº</th>
<th>Wall Thickness (mm)</th>
<th>Load (kN)</th>
<th>Equiv. Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>8</td>
<td>639</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>8.15</td>
<td>651</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>12.5</td>
<td>725</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>12.4</td>
<td>728</td>
</tr>
</tbody>
</table>

Average: 688MPa
UNIVERSAL TESTING MACHINE
(3 Points Bending test)

Load (kN)
Tube 30X20mm
L=500mm

Deflection (mm)
TENSILE TESTS

Tensile test
material: F114
specimen: 15.2 mm diameter

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain (adimensional)</td>
<td>0</td>
<td>0,0025</td>
<td>0,005</td>
<td>0,0075</td>
<td>0,01</td>
<td>0,0125</td>
<td>0,015</td>
</tr>
</tbody>
</table>

Stress-strain curve for specimen F114.
EXPERIMENTAL BUCKLING OF H.C (USING TUBULAR RODS)

ADVANTAGES:

1- H.C WEIGHT REDUCTION

2- ECONOMICAL IMPACT

3- ON-LINE MONITORING (SENSORS INSIDE ROD)

4- AESTHETIC ASPECT
<table>
<thead>
<tr>
<th>Tube thickness</th>
<th>Pin Diameter</th>
<th>Test N°</th>
<th>Buckling Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 mm</td>
<td>22 mm</td>
<td>4</td>
<td>32,75 kN</td>
</tr>
<tr>
<td>3 mm</td>
<td>22 mm</td>
<td>5</td>
<td>31 kN</td>
</tr>
<tr>
<td>3 mm</td>
<td>25,6 mm</td>
<td>3</td>
<td>68,38 kN</td>
</tr>
<tr>
<td>3 mm</td>
<td>25,6 mm</td>
<td>6</td>
<td>72,1 kN</td>
</tr>
<tr>
<td>5 mm</td>
<td>22 mm</td>
<td>11</td>
<td>42,68 kN</td>
</tr>
<tr>
<td>5 mm</td>
<td>22 mm</td>
<td>12</td>
<td>43,49 kN</td>
</tr>
<tr>
<td>5 mm</td>
<td>25,6 mm</td>
<td>10</td>
<td>97,16 kN</td>
</tr>
</tbody>
</table>
### EXPERIMENTAL LOAD vs EULER LOAD

- Tubular rods 30/24mm
- Frictionless boundary conditions
  
  (SAME PIPE but DIFFERENT ROD LENGTH)

<table>
<thead>
<tr>
<th>H.C Length (mm)</th>
<th>Experimental Load (kN)</th>
<th>EULER Load (kN)</th>
<th>Relative &quot;Error&quot; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1220</td>
<td>49</td>
<td>31.1</td>
<td>36.53</td>
</tr>
<tr>
<td>1320</td>
<td>36.8</td>
<td>26.6</td>
<td>27.713</td>
</tr>
<tr>
<td>1420</td>
<td>29</td>
<td>23</td>
<td>20.68</td>
</tr>
<tr>
<td>1645</td>
<td>18.4</td>
<td>17.1</td>
<td>7.06</td>
</tr>
</tbody>
</table>
EXPERIMENTAL H.C BUCKLING SUMMARY

Frictionless boundary conditions (Joint pin 22mm)

Tubular rods 30/24mm

Critical Load (kN)

Evolution of the critical load with the length of the cylinder (joint pin 22 mm)

Standard length

H.C Length (mm)
Evolución de la de carga crítica con la longitud del cilindro (pasador 25,6)

Critical Load (kN)

H.C Length (mm)

WITH FRICTION

- Tube-Exp.
- Euler (tubo)
- Euler (barra)
- carga de pandeo tubo experimental
- carga de pandeo barra experimental
- Standard
**SUMMARY RESULTS**

**HYDRAULIC CYLINDERS**

Buckling of hydraulic cylinder

L = 1220 mm

Buckling of simple rods

L = 1350 mm
BUCKLING OF TUBE RODS FILLED WITH CERAMIC MATERIAL

BCE-UPC
BUCKLING TEST BENCH
Bi-articulated rod (diam. 6mm) (L= 250 mm)

Force cell (5000 pounds)
Bi-Clamped rod (6mm diameter)
BUCKLING TEST RESULTS - RODS

Compr. Force (N)

- pin-pin
- lamp-clamp
- lamp-clamp
- pin-pin
- lamp-clamp
- lamp-clamp
- pin-pin
- lamp-clamp
- lamp-clamp

Full section  Annular section  Annular+Ceramic

Euler model
FIELD TESTS

• Indoor test with backhoe (HIDRAR/UPC) (cylinders and rods)

• Field test with backhoe (HIDRAR-BMH)
Indoor tests with backhoe (HIDRAR/UPC) (cylinders and rods)
BACKHOE FRAME
Cylinder substituted by a simple rod (for buckling purposes)

MASTER CYLINDER
Mechanical advantage = 8
## Rod test on backhoe machine

<table>
<thead>
<tr>
<th>Rod</th>
<th>D ext</th>
<th>D int</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>FULL SECTION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td></td>
<td>1.240</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td></td>
<td>1.240</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td></td>
<td>1.240</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td></td>
<td>1.240</td>
</tr>
<tr>
<td>ANNULAR SECTION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>9</td>
<td></td>
<td>1.240</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td></td>
<td>1.240</td>
</tr>
<tr>
<td>25</td>
<td>19</td>
<td></td>
<td>1.240</td>
</tr>
<tr>
<td>30</td>
<td>24</td>
<td></td>
<td>1.240</td>
</tr>
</tbody>
</table>
Rod buckling (stick movement) on backhoe

- Starting torque curve
- Torque curve (just before buckling)

![Diagram showing stress and pressure curves with labeled points 1 to 4 and corresponding labels for torque and pressure](image)
FARM LOADER
ISO 13.725
Excel sheet application

### PARÁMETROS DEL ACTUADOR

<table>
<thead>
<tr>
<th>Referencia</th>
<th>Longitud del cilindro</th>
<th>Diámetro Exterior</th>
<th>Diámetro interior</th>
<th>Módulo de elasticidad</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0,8 m</td>
<td>d1 e</td>
<td>0,06 m</td>
<td>2,00E+11 Pa</td>
</tr>
<tr>
<td>L2</td>
<td>0,6 m</td>
<td>d1 i</td>
<td>0,05 m</td>
<td>2,00E+11 Pa</td>
</tr>
</tbody>
</table>

### VASTAGO

<table>
<thead>
<tr>
<th>Longitud que sale el vástag</th>
<th>Lvas</th>
<th>0,7 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>diámetro del vástag</td>
<td>d2</td>
<td>0,03 m</td>
</tr>
<tr>
<td>Módulo de elasticidad</td>
<td>e2</td>
<td>2,00E+11 Pa</td>
</tr>
</tbody>
</table>

### Datos de diseño

- excentricidad de carga: e_off_axis = 2 mm
- Tensión de fluencia: sigma_e = 3,49E+08 Pa
- factor de seguridad: k = 1

**Carga Crítica de pandeo**

- 70.55 kN

**Carga máxima admisible**

- 339.63 MPa

**Tensión a comp simple**

- 55.8 kN

**Carga de Euler**

- 79.93 MPa

**PARAMETROS a Fmax admisible**

<table>
<thead>
<tr>
<th>Ra</th>
<th>-44,684 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rbc</td>
<td>-8,148 N</td>
</tr>
<tr>
<td>Rd</td>
<td>40,587 N</td>
</tr>
<tr>
<td>Ma</td>
<td>N m</td>
</tr>
<tr>
<td>Md</td>
<td>N m</td>
</tr>
<tr>
<td>Mbc</td>
<td>-678,455 N m</td>
</tr>
<tr>
<td>t0</td>
<td>0,18294 grados</td>
</tr>
<tr>
<td>psi_a</td>
<td>0,79887 grados</td>
</tr>
<tr>
<td>psi_d</td>
<td>0,94516 grados</td>
</tr>
<tr>
<td>phi_a</td>
<td>0,00000 grados</td>
</tr>
<tr>
<td>phi_b</td>
<td>0,17946 grados</td>
</tr>
<tr>
<td>phi_c</td>
<td>-1,31263 grados</td>
</tr>
<tr>
<td>phi_d</td>
<td>0,00000 grados</td>
</tr>
</tbody>
</table>

**Tipos de montaje**

- apoyado - apoyado
- empotrado - apoyado
- apoyado - empotrado
- empotrado - empotrado
- empotrado - libre
- empotrado - libre(emp)
FINAL CONCLUSIONS

1- ISO Standard 13725 does not include the misalignments and adherence pin/bushing friction effects.
2- adherence or friction pin/bushing represent a factor of 3 compared with ideal bi-articulated joints.
3- hydraulic cylinder own weight (aprox 100 N) has a negligible influence on load capacity (only 2% reduction of load capacity)
4- misalignment due to guide ring wear ( 5 % due to 1000 cycles) has a higher influence on load capacity (reduction of load capacity about 10 %)
5- In the hydraulic cylinder tested, an eccentric load of 1 mm, reduced the load capacity about 12 %
6- In real machines, mechanism layout can modify the hydraulic cylinder load capacity during the kinematics cycle due to the friction torques in pin/bushing joints. The friction torque can be an ACTIVE TORQUE or a PASSIVE TORQUE, depending on mechanism kinematics. This innovative result has been demonstrated by the experimental buckling results experiments applied on real machines (Farm loader and Backhoe).
7- Buckling experimental results showed that tubular rods filled with ceramic material did not gave the expected results
ACHIEVEMENTS BEYOND THE STATE OF THE ART

• A theoretical model for different boundary conditions was developed and experimentally validated, describing the cylinder load capacity, including all those important factors affecting its load capacity, such as:
  • Misalignment between cylinder rod and cylinder body due to assembly tolerances
  • Misalignment due to guide rings wear
  • Misalignment due to oil pressure
  • Frictions at end bearing supports and
  • Cylinder own weight.
• ISO 13725 Excel sheet application for different boundary conditions has been developed.
• Several typographic mistakes have been detected in ISO 13725 and should be transmitted to ISO Committee through UNACOMA/AIFTOP.
• The mathematical model is implemented by Excel worksheet, using Visual Basic software, for load capacity and piston-rod diameter evaluations.
• Experimental data base creation with more than 100 hydraulic cylinders which have been destructed using the buckling test bench for cylinder’s load capacity calculation.
• Experimental results on real machines (Farm loader and Backhoe) demonstrated that layout can modify the hydraulic cylinder load capacity during the kinematics cycle, due to the friction torque in pin/bushing joints.