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)

6. Collaboration with IFTR and ROQUET for a new design method for H.C based on probabilistic design

7. Field Tests: (Collaboration with HIDRAR)
   - Indoor test with backhoe (HIDRAR/UPC) (cylinders and rods)
   - Field test with backhoe (HIDRAR-BMH)

STATE OF THE ART	year	Factors Affecting Actuator Load Capacity					
		EXP	Initial Imperfection	Friction Torques	Load Eccentricity	Actuator Weight	Fluid
Hoblit, Fred. Critical buckling for hydraulic actuating cylinders.	1950		is considered				is considered
K.L Seshasai Stress Analysis of Hydraulic Cylinders.	1975		as initial data				is considered (Hoblit)
Bennett, M.C A Calculation of Piston rod Strength.	1978		as initial data	only for piston rod articulation		reaction in piston rod articulatio n	
Ravishankar, N. Finite Element Analysis of Hydraulic Cylinders.	1980		elastic rigidity in connection point			as a distributed load	
Chai Hong Yoo Column loadings on telescopic power cylinders.	1986		through FEM		through FEM	through FEM	
S. Baragetti Bending behaviour of double-acting hydraulic actuators.	2001		initial definition as sinusoidal	Equivalents for both sides			
Norma ISO/TS 13725 (ISO/TC131 subcom. SC3)	2001				is considered	is considere d	is considered (Hoblit)
Yishou T., Wenwei, W. Stability analysis for hydraulic hoist cylinder of	2004		is considered			distributed load in tube and	is considered (Hoblit)

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)

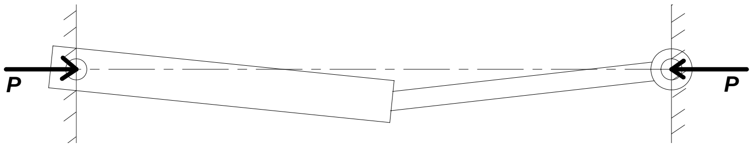
2- Interaction in pin/bushing joint (Friction)

- Friction torques in hydraulic cylinder end joints

3-Mechanism layout effect on load capacity

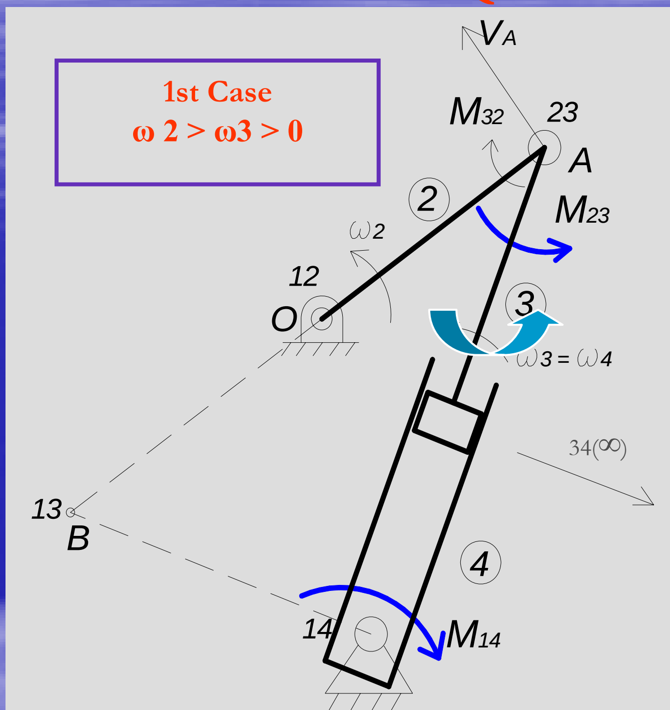
THEORETICAL MODEL MATRIX

$$
\begin{pmatrix}
sen(k_1L_1) & 0 & 0 & -1 & 0 & \frac{L_2}{PL}-\frac{\cos(k_1L_1)}{P} & \frac{L_1}{PL} \\
0 & \cos(k_2L) & \text{sen}(k_2L) & 0 & 0 & 0 & \frac{1}{P} \\
0 & \cos(k_2L_1) & \text{sen}(k_2L_1) & -1 & 0 & \frac{L_2}{PL} & \frac{L_1}{PL} \\
-k_1\cos(k_1L_1) & -k_2\text{sen}(k_2L_1) & k_2\cos(k_2L_1) & 0 & -1 & -\frac{k_1\text{sen}\left(k_1L_1\right)}{P} & 0 \\
0 & 0 & 0 & K_CP & 0 & -K_C\frac{L_2}{L} & -K_C\frac{L_1}{L} \\
k_1 & 0 & 0 & 0 & 0 & -\frac{1}{PL} & \frac{1}{PL} \\
0 & -k_2\text{sen}(k_2L) & k_2\cos(k_2L) & 0 & 0 & -\frac{1}{PL} & \frac{1}{PL}
\end{pmatrix}
\begin{pmatrix}
C_1 \\ C_2 \\ C_3 \\ Y_c \\ \theta \\ M_{e1} \\ M_{e2}
\end{pmatrix}
\begin{pmatrix}
\frac{q_1\cos(k_1L_1)}{Pk_1^2}+\frac{QL_1}{PL}-\frac{q_2L_1L_2}{P}-\frac{q_1L_1^2}{2P}-\frac{q_1}{k_1^2P} \\
\frac{Q}{P}-\frac{q_2L^2}{2P}-\frac{L_1^2}{2P}(q_1-q_2)-\frac{q_2}{k_2^2P} \\
\frac{QL_1}{PL}-\frac{q_2L_1L}{P}-\frac{L_1^2}{P}\left(\frac{q_1}{2}-q_2\right)-\frac{q_2}{k_2^2P} \\
\frac{q_1}{Pk_1}\text{sen}\left(k_1L_1\right) \\
\theta_1+K_C\left(\frac{q_1L_1^2}{2}+q_2L_1L_2-\frac{QL_1}{L}\right) \\
-\frac{Y_{0C}}{L_1}-\frac{1}{P}\left[q_1L_1+q_2L_2-\frac{Q}{L}\right] \\
\frac{Y_{0C}}{L_2}+\frac{Q}{PL}
\end{pmatrix}
$$



Actuator as a component of the mechanism

M23 is ACTIVE TORQUE

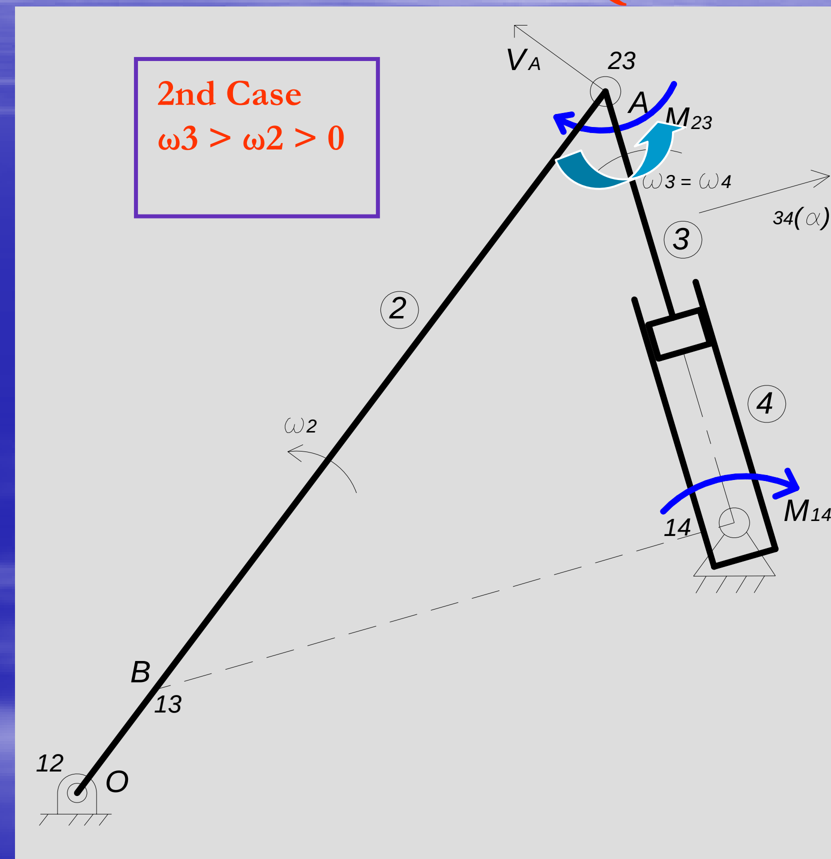


ANG. VELOCITY of rod is **positive** and

TORQUE in rod pin is **positive** →

ROD TORQUE POWER IS **POSITIVE**

M23 is RESISTIVE TORQUE



ANG. VELOCITY of rod is **positive** and

TORQUE in rod pin is **negative** →

ROD TORQUE POWER IS **NEGATIVE**

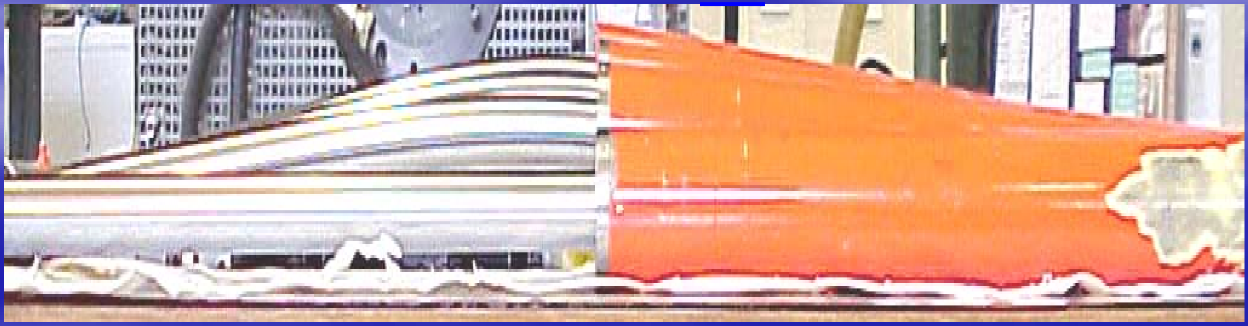
Previous Experimental work

Experiments with hydraulic cylinders

ROD DIAMETER : 30mm

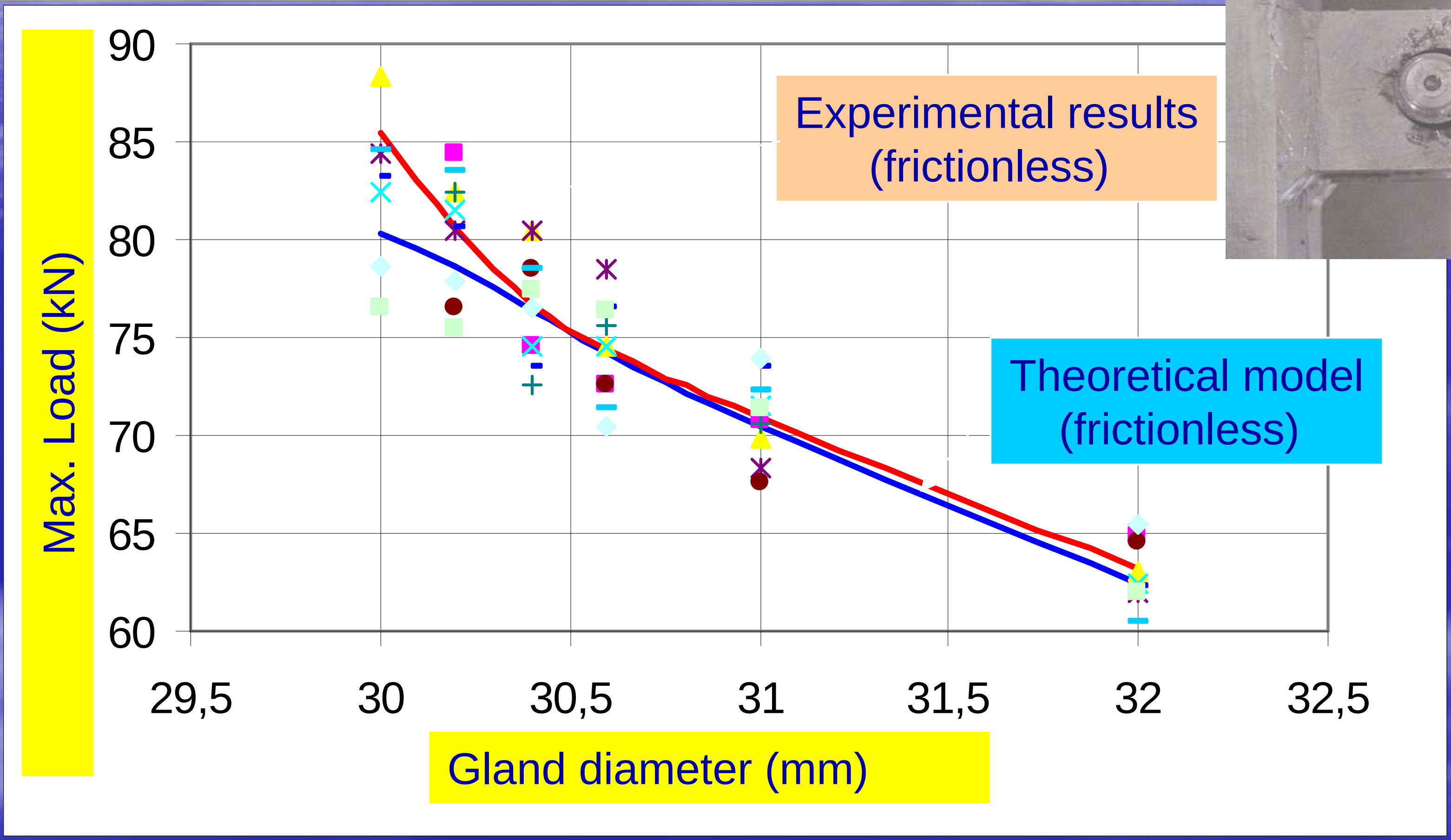
GLAND DIAMETER :

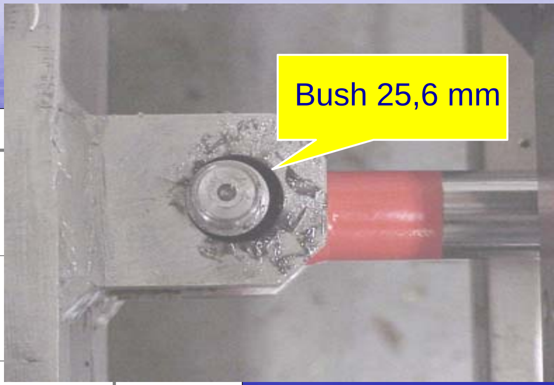
30 30,2 30,4 30,6



Theoretical Model vs Experimental Results (frictionless)

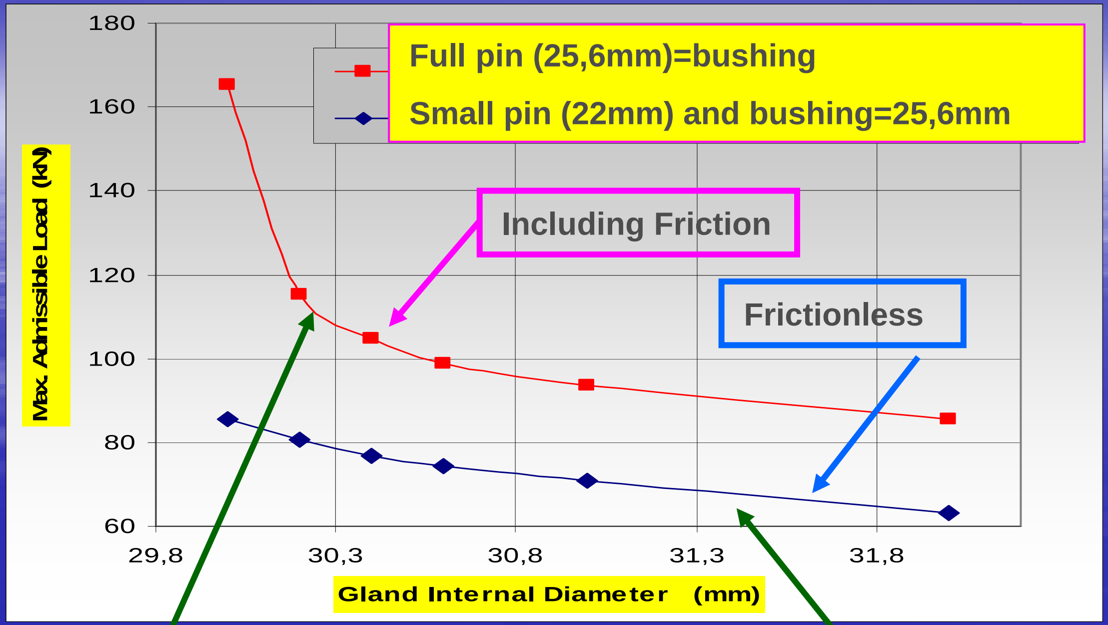
Pin diameter = 22mm and bush diameter = 25,6 mm



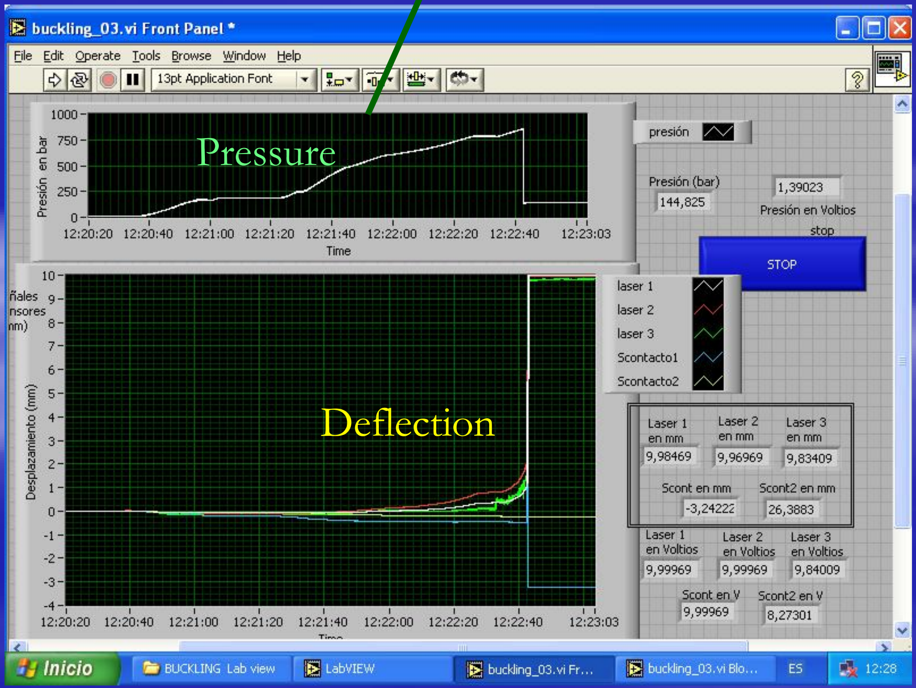


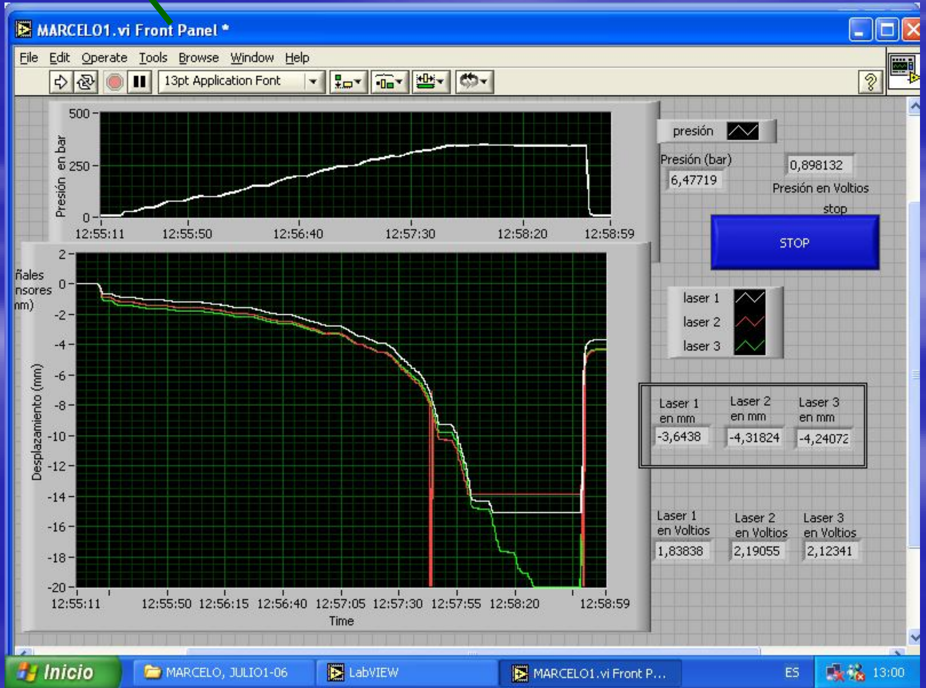
Gland mm	30	30,2	30,4	30,6	31	32
Misalig. Angle (º)	0,136	0,198	0,275	0,341	0,473	0,802

FRICTION and FRICTIONLESS JOINTS COMPARISON

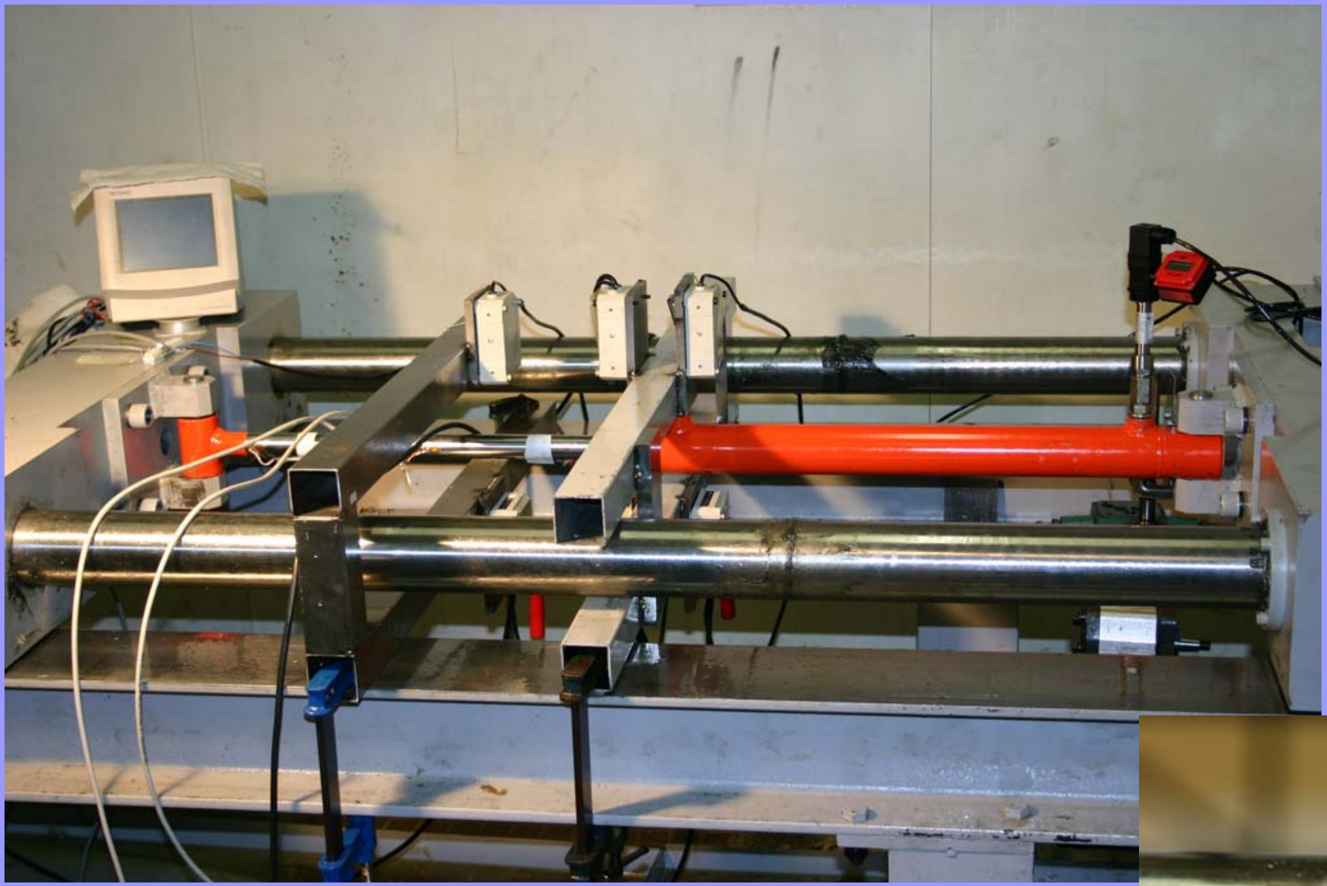


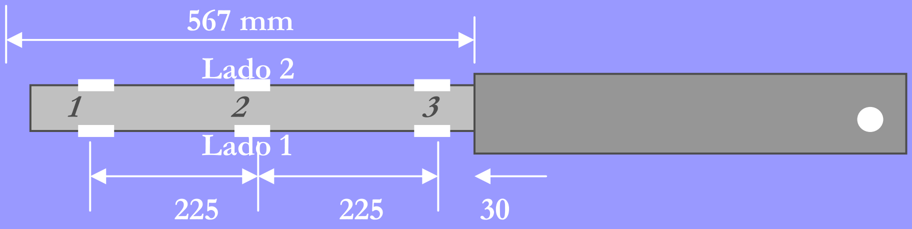
Gland Diameter (mm)	Θ_1 (grades)
30	0,136
30,2	0,198
30,4	0,275
30,6	0,341
31	0,473
32	0,802



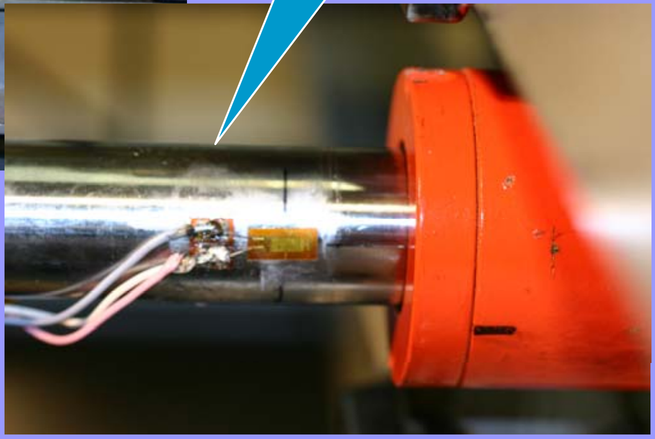


Strain gauges for bending moment measurement along the rod

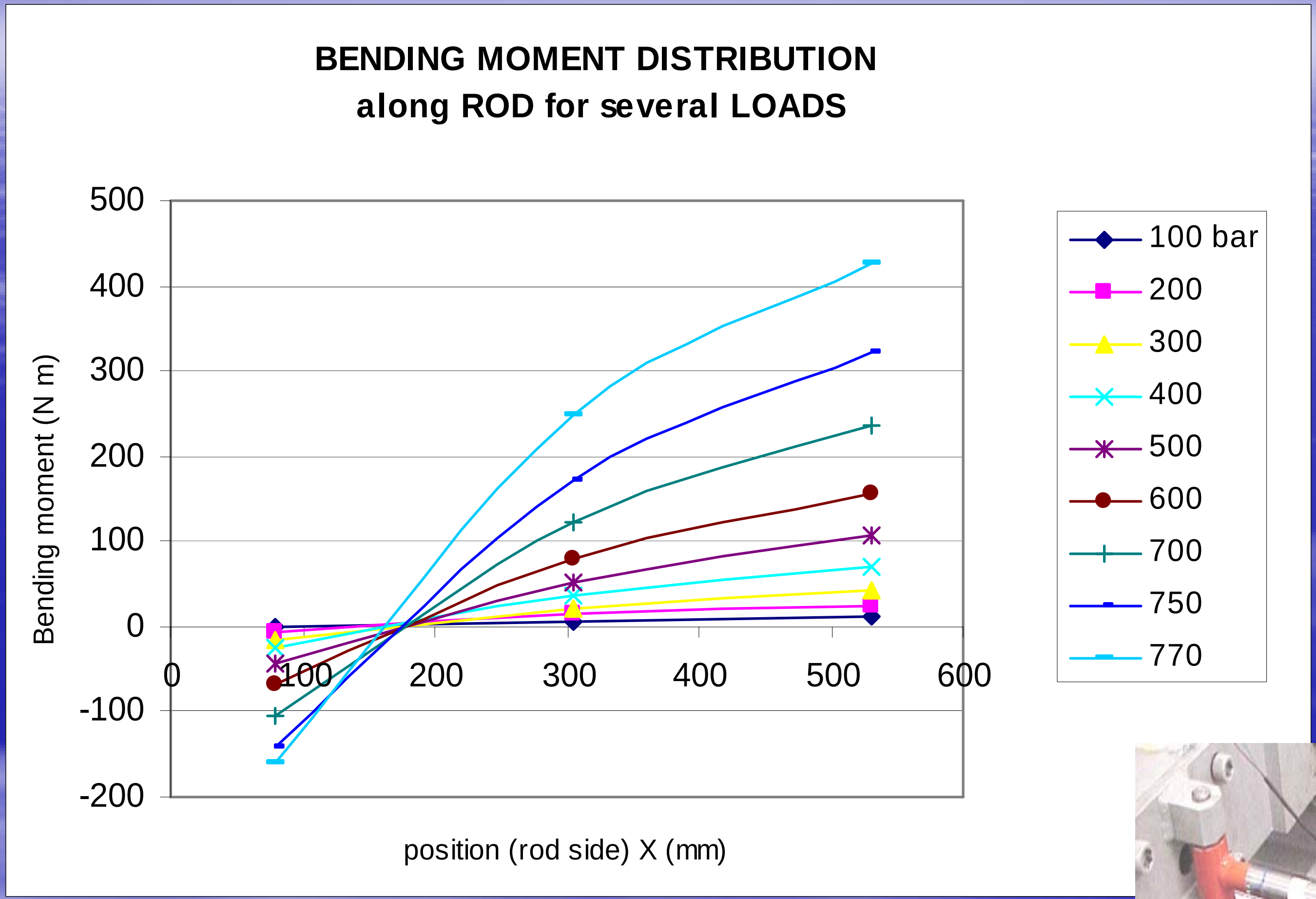


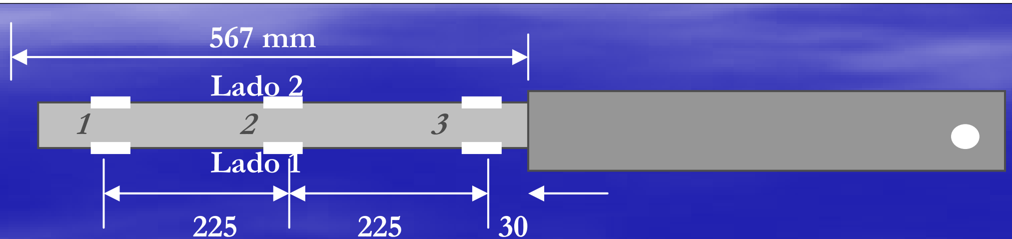


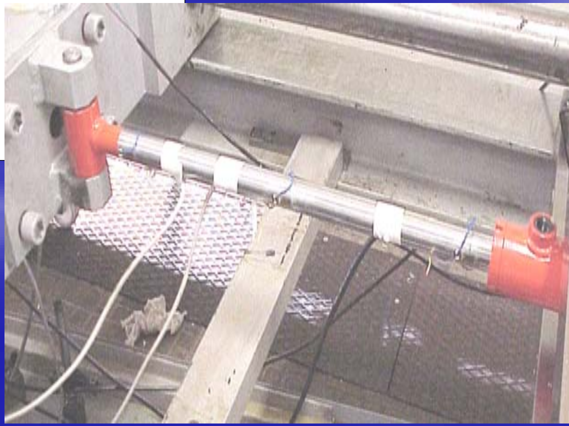
STRAIN GAUGES



Bending torques measured through strain gauges

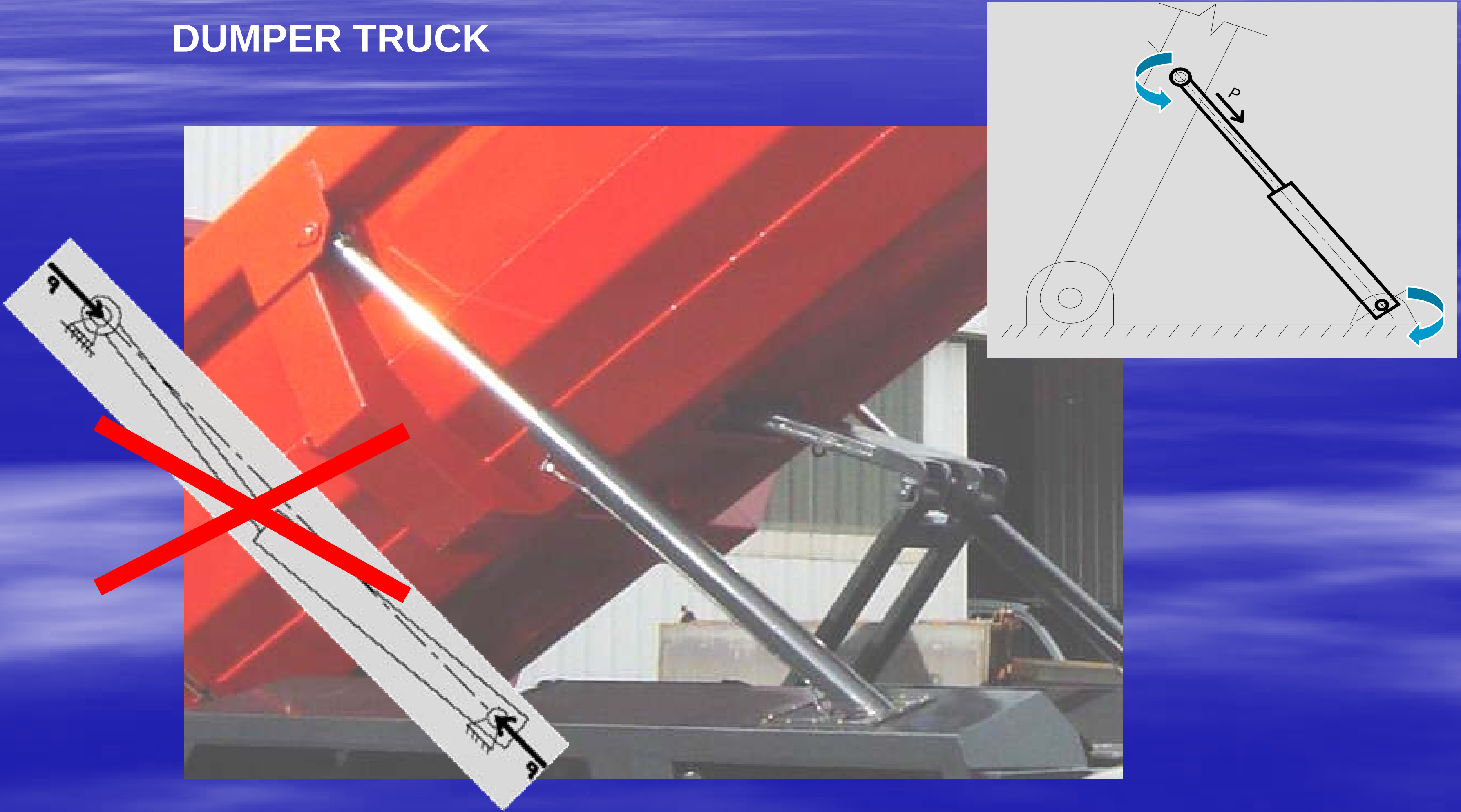


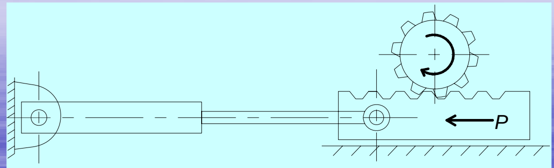
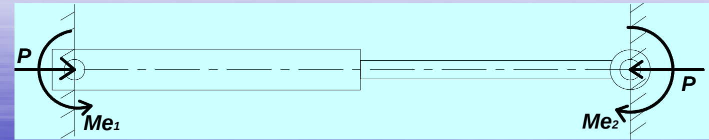


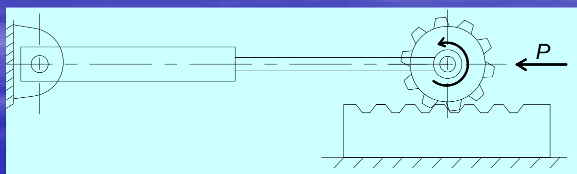
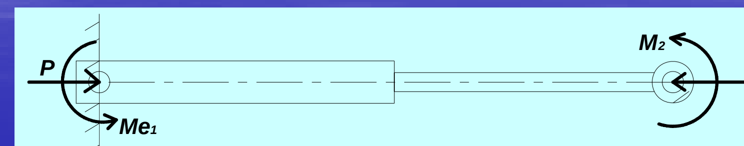


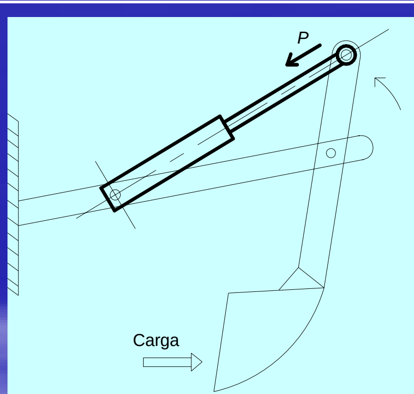
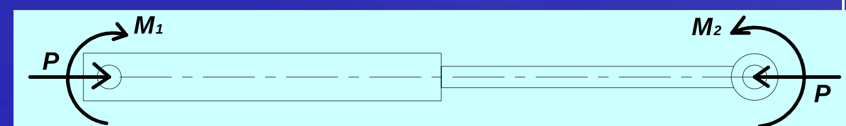
REAL BI-ARTICULATED CYLINDERS

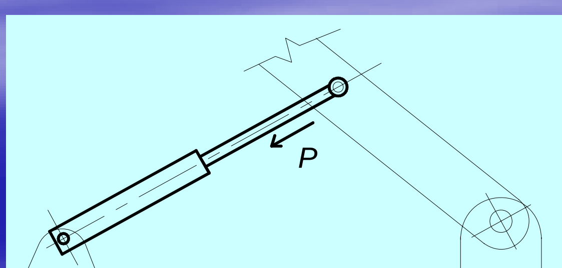
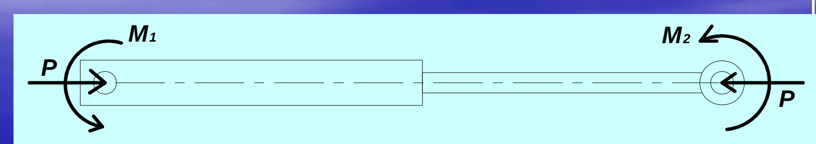
DUMPER TRUCK



<table>
<tr><th>Mechanisms (examples)</th><th>Real behaviour</th></tr>
<tr><td>
</td><td>

bi-articulated</td></tr>
<tr><td>
</td><td>

Clamped-articulated with torques</td></tr>
<tr><td>
</td><td>

bi-articulated with torques of different sense</td></tr>
<tr><td>
</td><td>

Bi-articulated with torques of same sense</td></tr>
</table>

WORK PERFORMED DURING THE LAST PERIOD (37- 48 months)

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

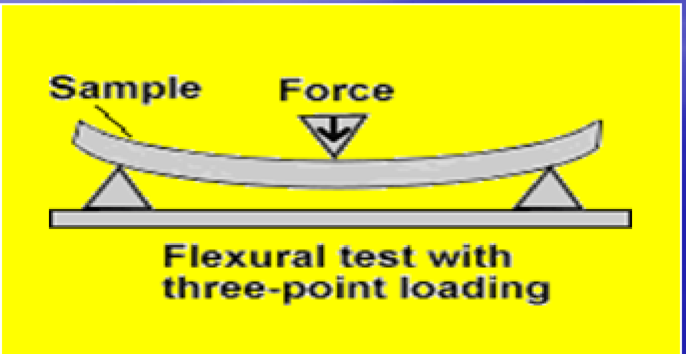
UNIVERSAL TESTING MACHINE
(3 Points Bending test)

TUBE ROD

H.Tubes St 37

30X20 and 30X24mm

L= 500mm

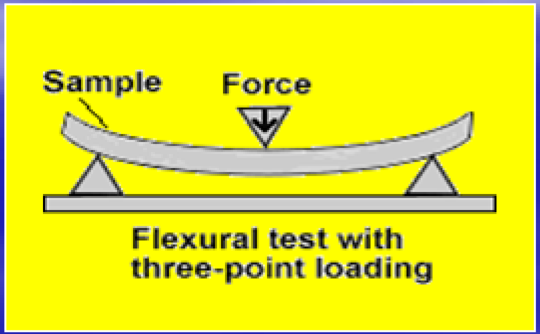


BENDING STRESS DETERMINATION

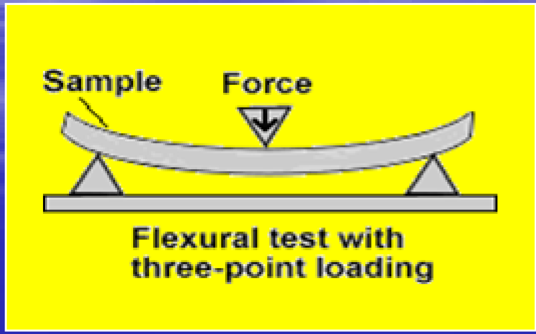
(TUBE AND BAR ROD BENDING TESTS)

BAR ROD

Rod F-114
30mm diameter
L= 500mm



.EXPERIMENTAL BENDING RESULTS WITH BAR RODS
(30mm diameter and L=500mm)



Test Nº	Machine (Limit force) (kN)	Max. load (Elastic Zone) (kN)	Equivalent Stress (MPa)
1	25	15	707
2	200	14	660

Average: 684MPa

EXPERIMENTAL RESULTS WITH TUBULAR RODS

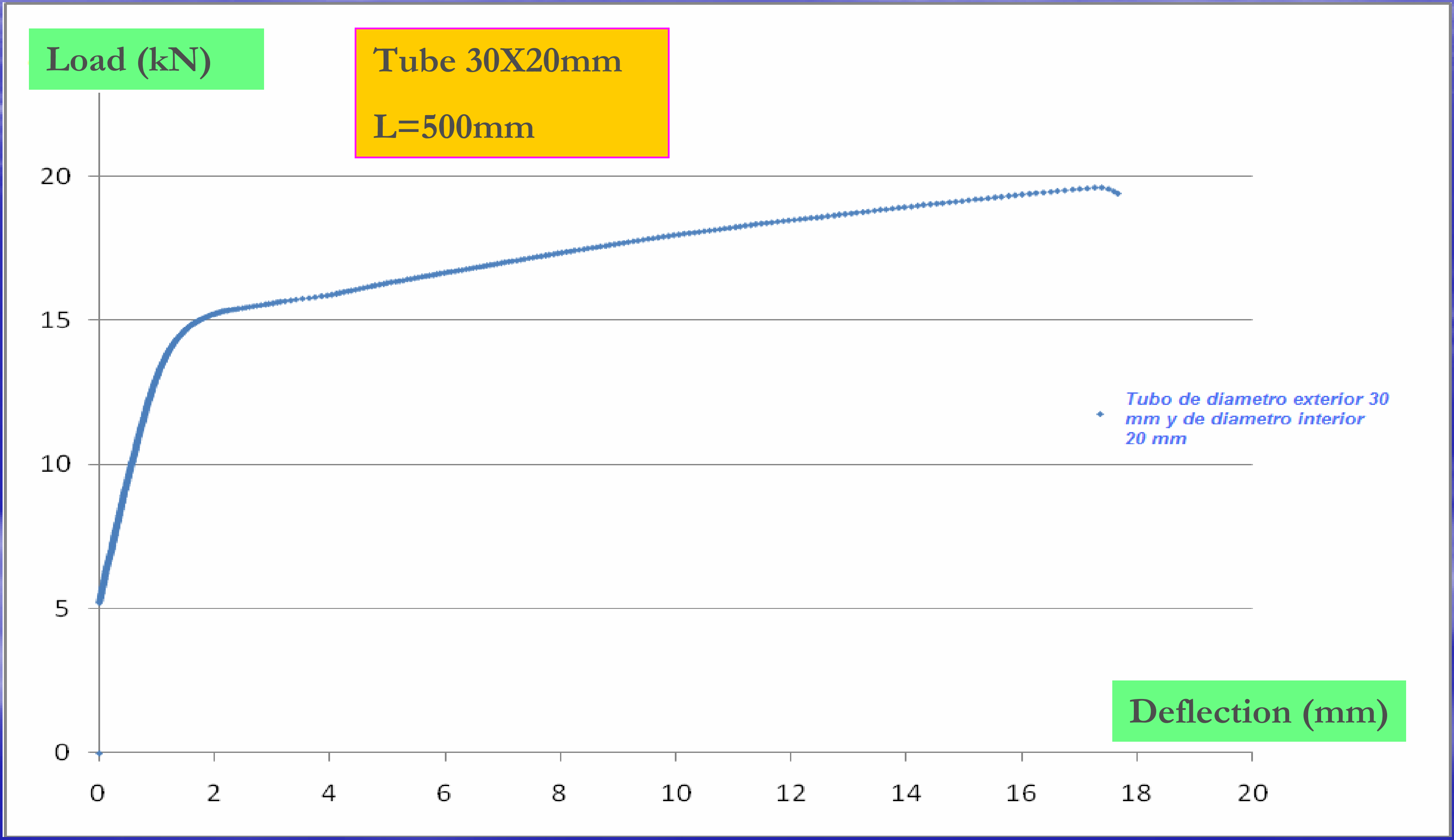
(30/24 and 30/20 mm external/internal diameters)

Tube Nº	Wall Thickness (mm)	Load (kN)	Equiv. Stress (MPa)
1	3	8	639
2	3	8,15	651
3	5	12,5	735
4	5	12,4	728

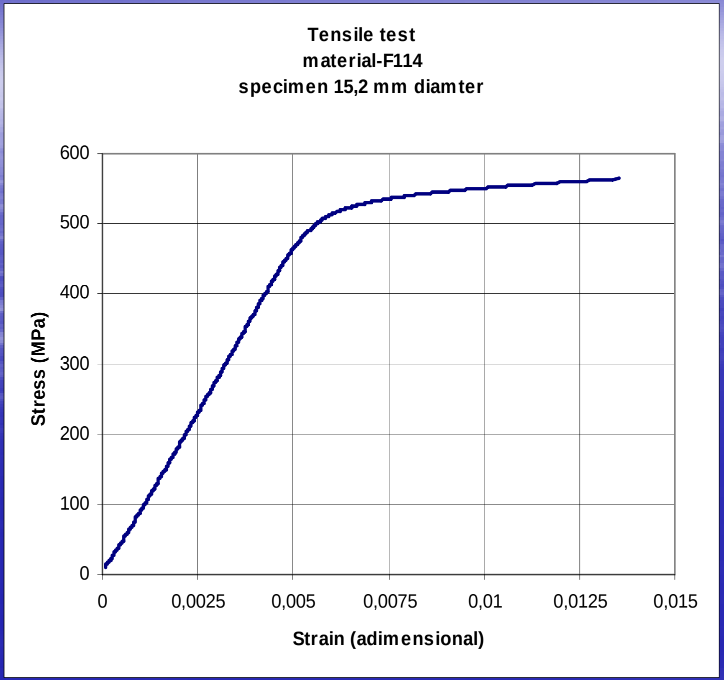
Average: 688MPa

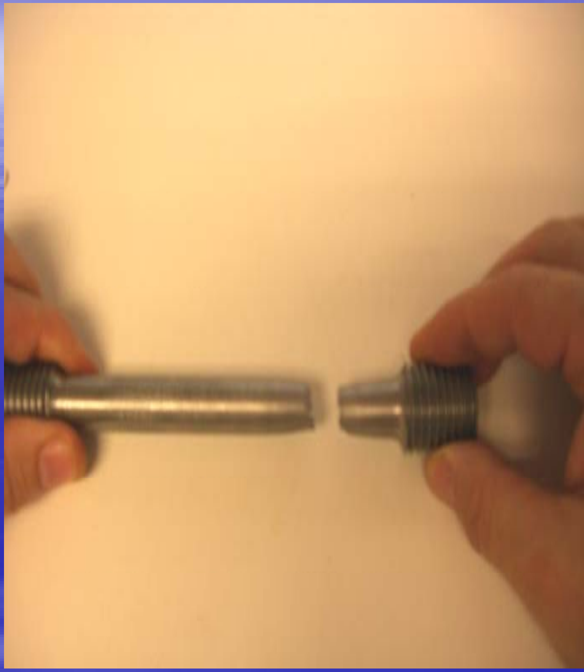
UNIVERSAL TESTING MACHINE

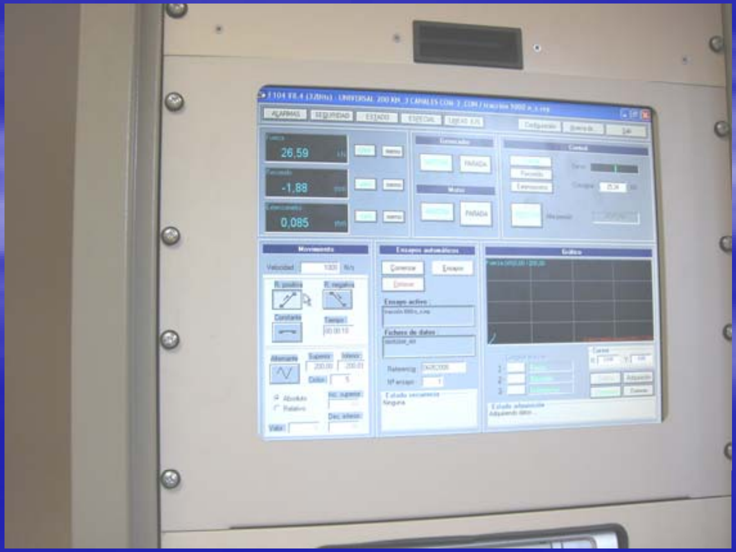
(3 Points Bending test)



TENSILE TESTS







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

TUBULAR RODS BUCKLING

(30mm external diameters)

Tube thickness	Pin Diameter	Test Nº	Buckling Load
3 mm	22 mm	4	32,75 kN
3 mm	22 mm	5	31 kN
3 mm	25,6 mm	3	68,38 kN
3 mm	25,6 mm	6	72,1 kN
5 mm	22 mm	11	42,68 kN
5 mm	22 mm	12	43,49 kN
5 mm	25,6 mm	10	97,16 kN

EXPERIMENTAL LOAD vs EULER LOAD

- Tubular rods 30/24mm
- Frictionless boundary conditions

(SAME PIPE but DIFFERENT ROD LENGTH)

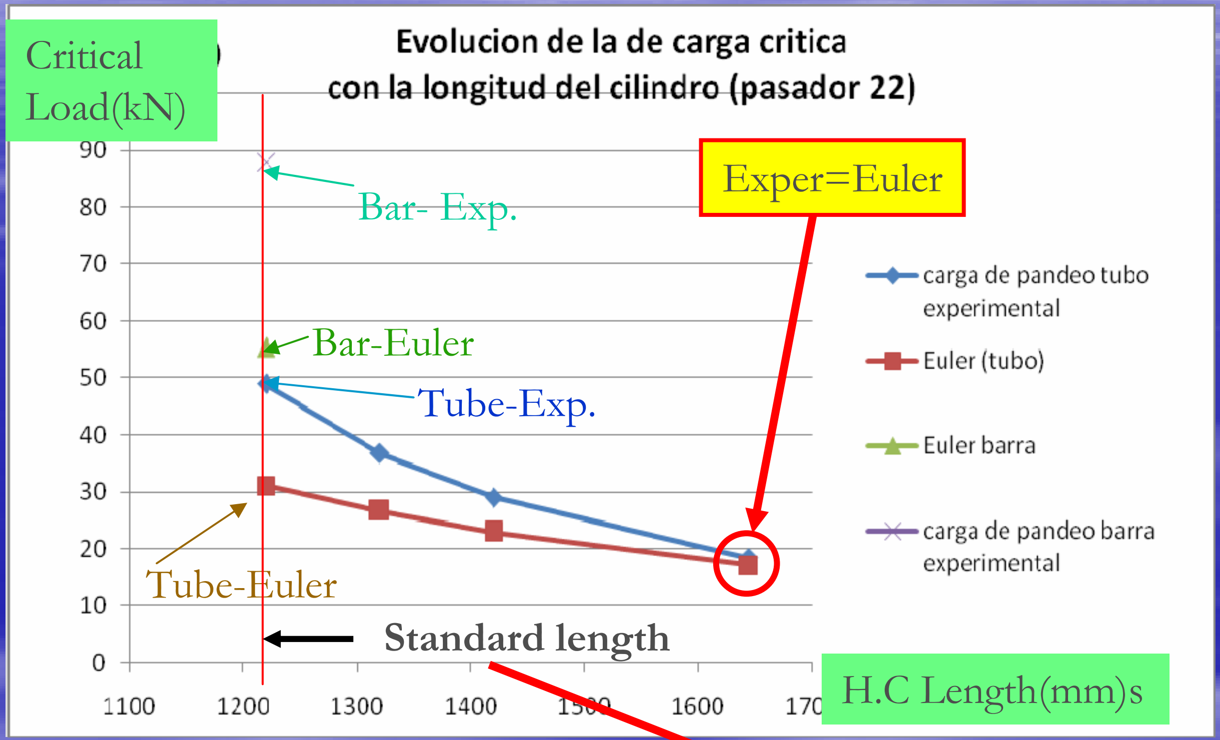
	H.C Length (mm)	Experimental Load (kN)	EULER Load (kN)	Relative "Error" (%)
Standard →	1220	49	31,1	36,53
	1320	36,8	26,6	27,713
	1420	29	23	20,68
	1645	18,4	17,1	7,06

EXPERIMENTAL H.C BUCKLING SUMMARY

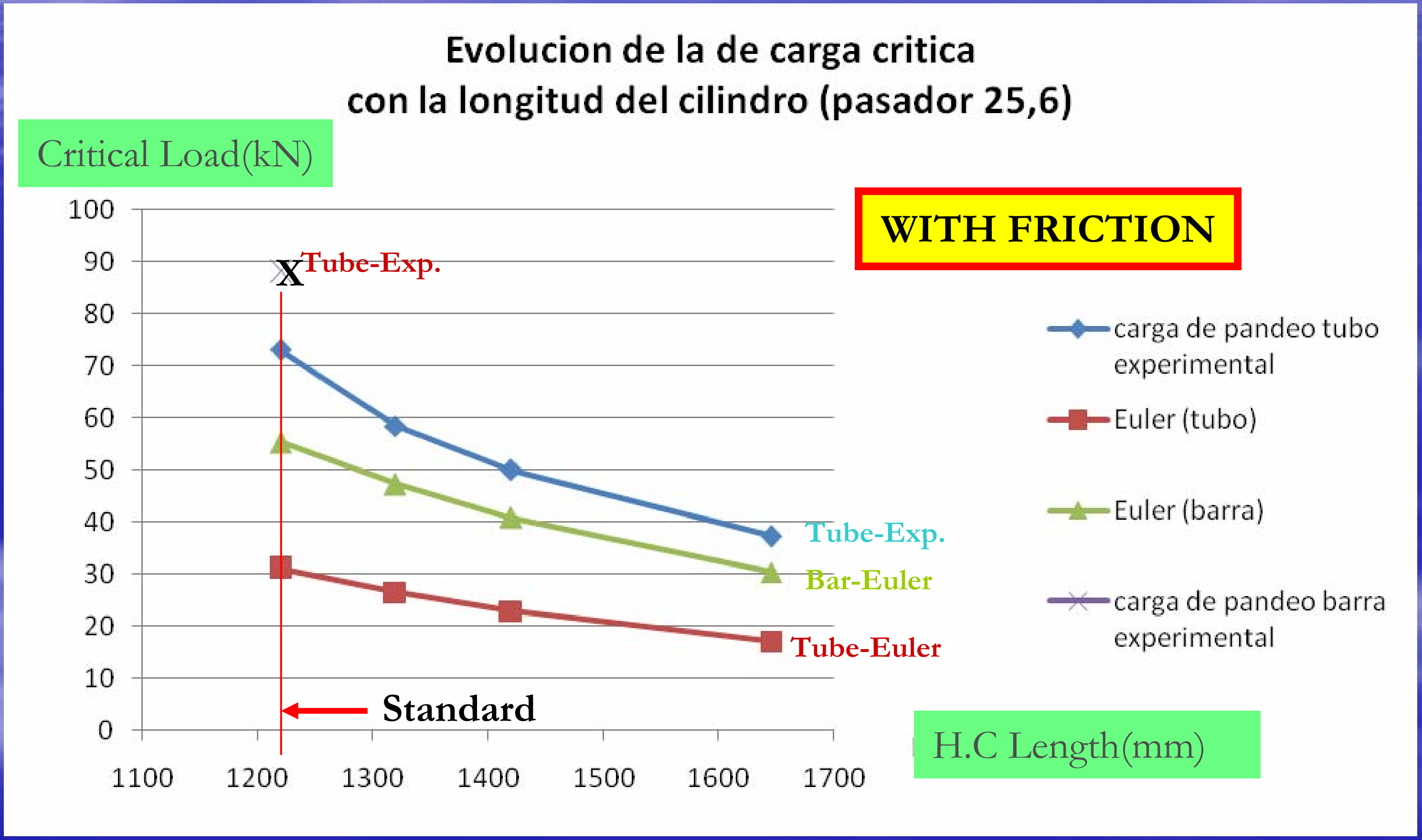
Frictionless boundary conditions (Joint pin 22mm)

Tubular rods 30/24mm

FRICTIONLESS

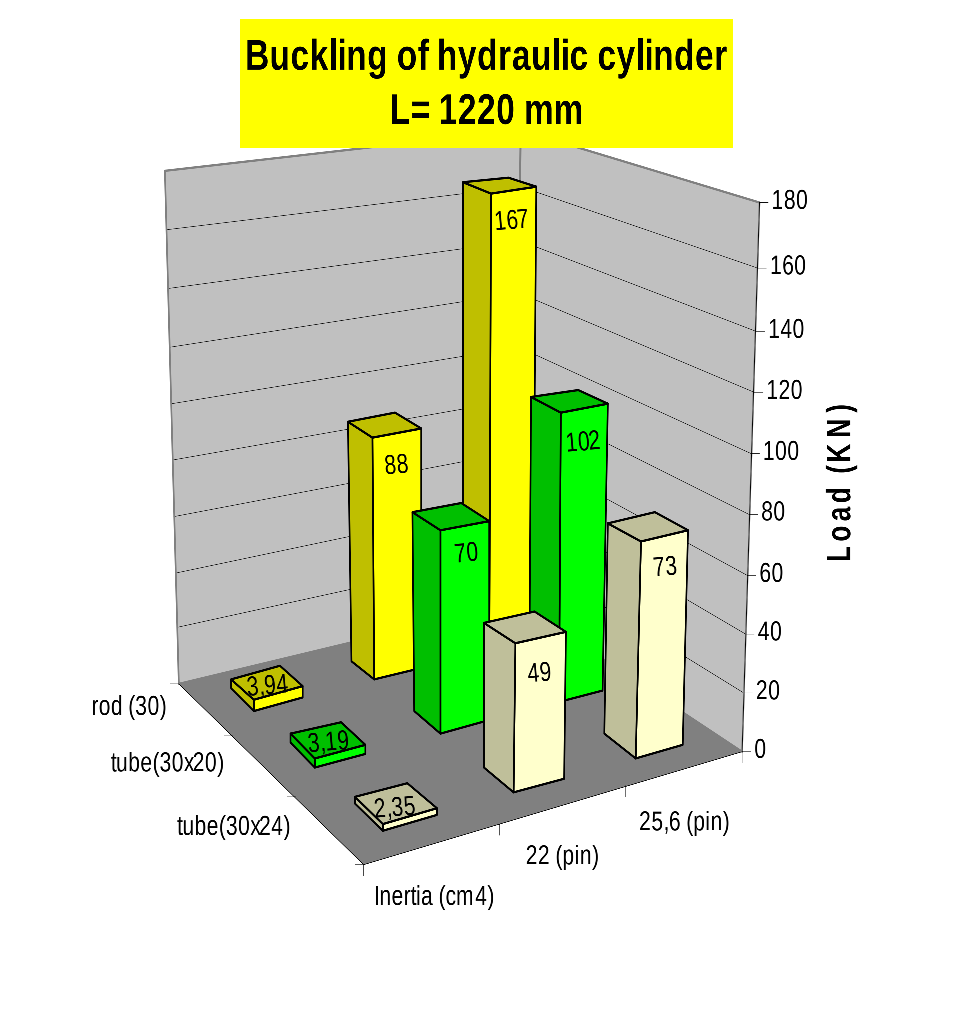


FRICTION BOUNDARY CONDITIONS (Pin joint 25,6mm)
Tubular Rod 30/24mm)

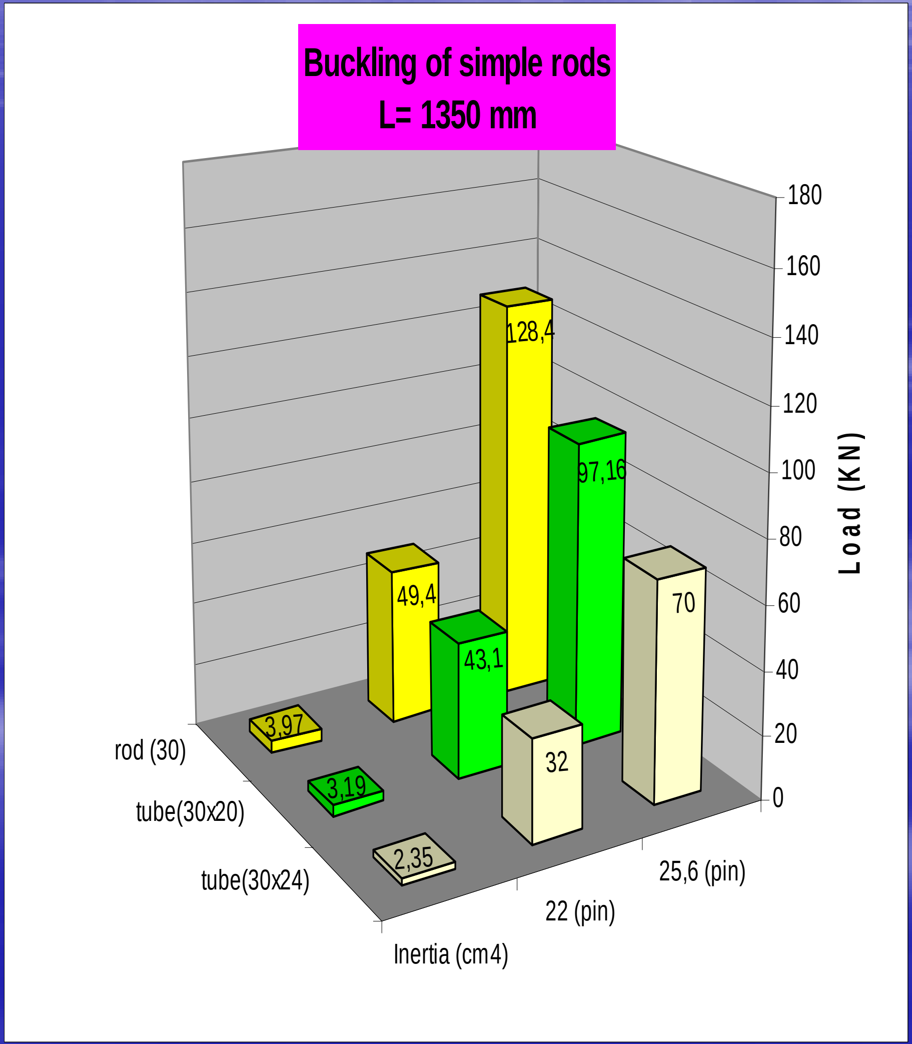


SUMMARY RESULTS

HYDRAULIC CYLINDERS



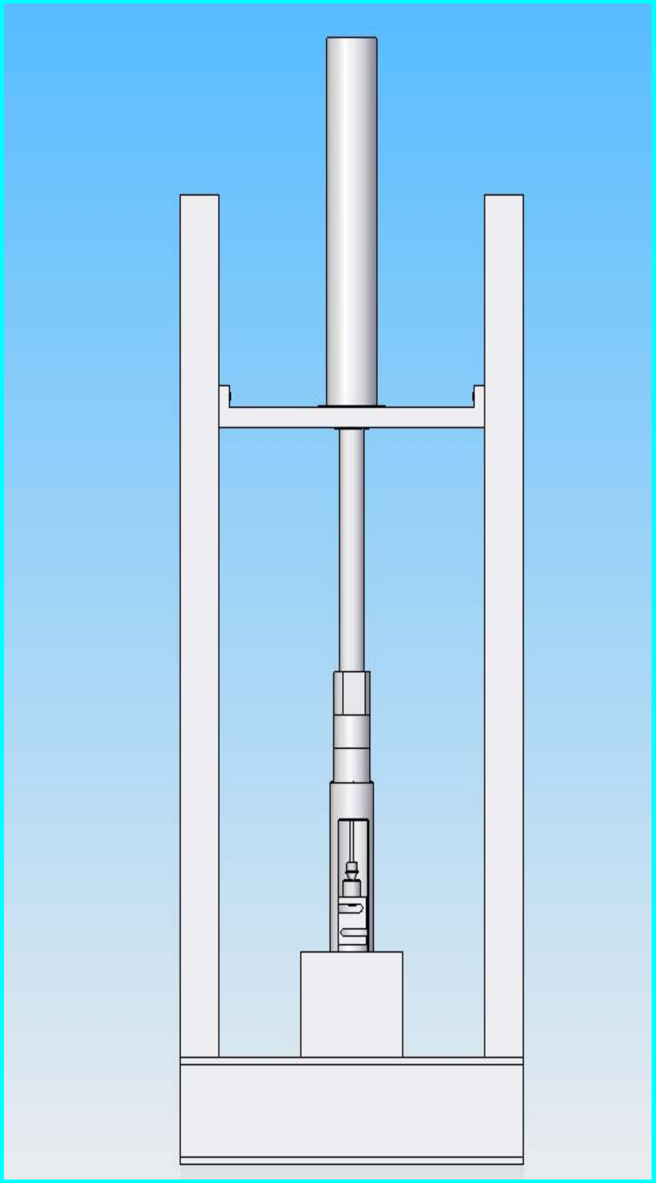
SIMPLE RODS



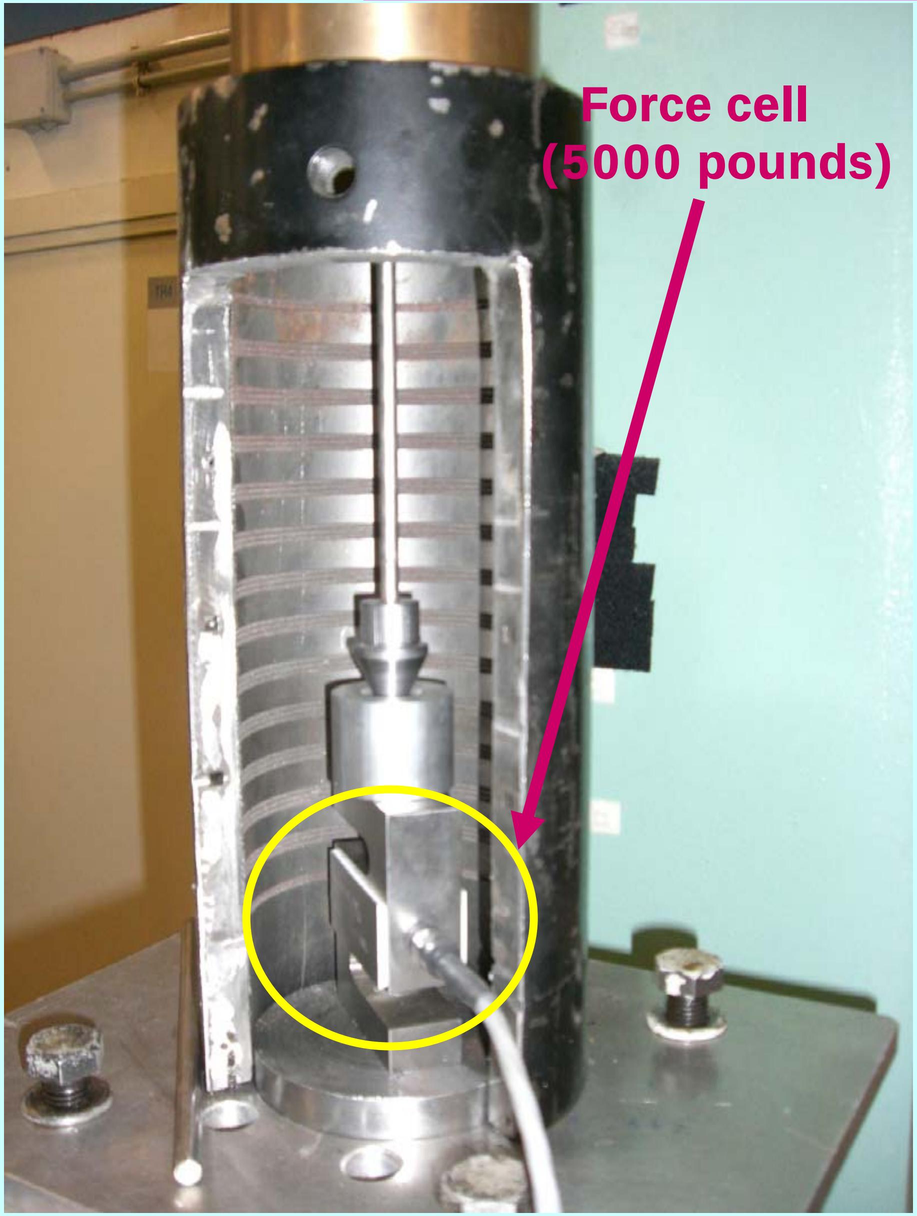
BUCKLING OF TUBE RODS FILLED WITH CERAMIC MATERIAL

BCE-UPC

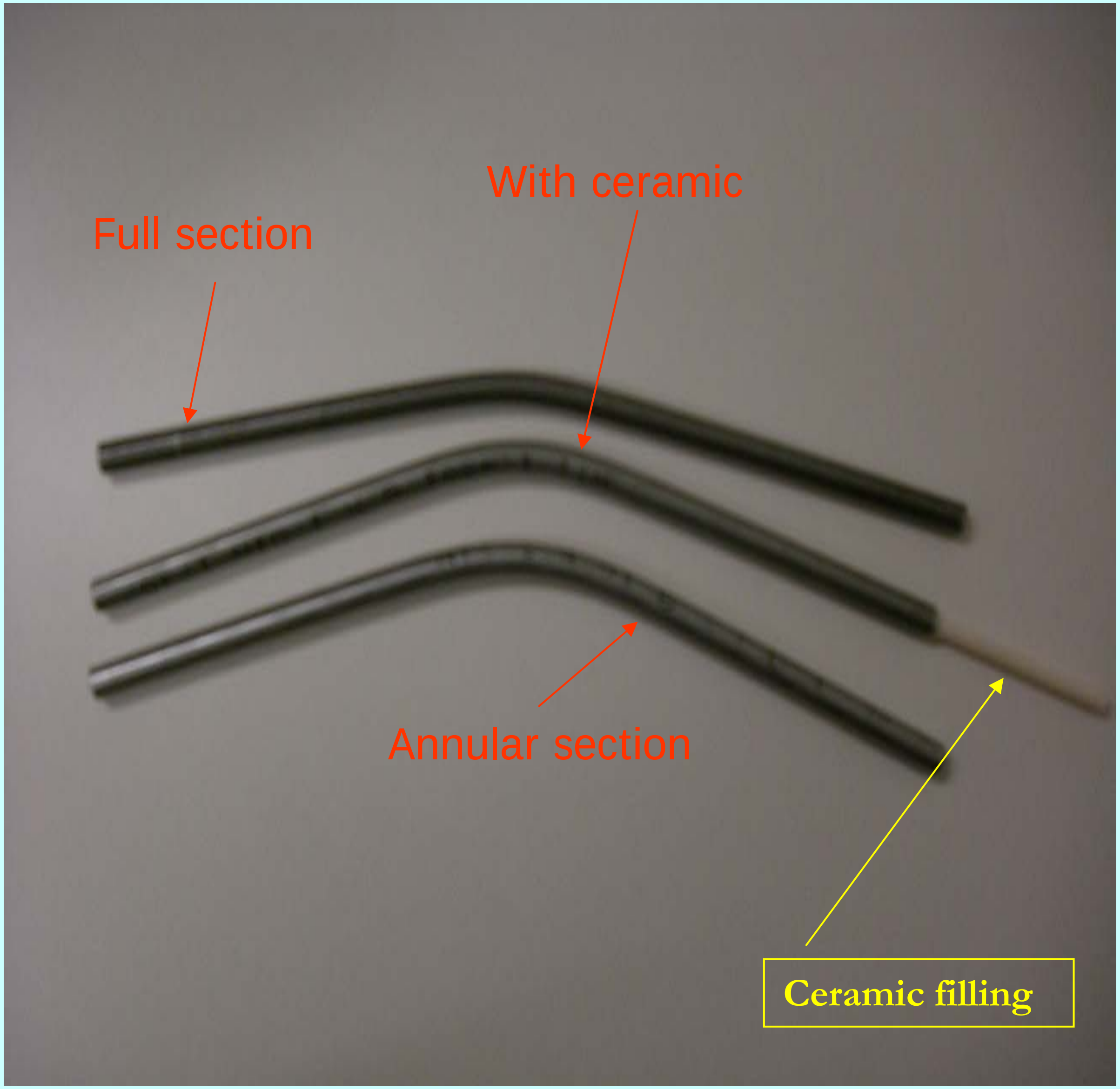
BUCKLING TEST BENCH



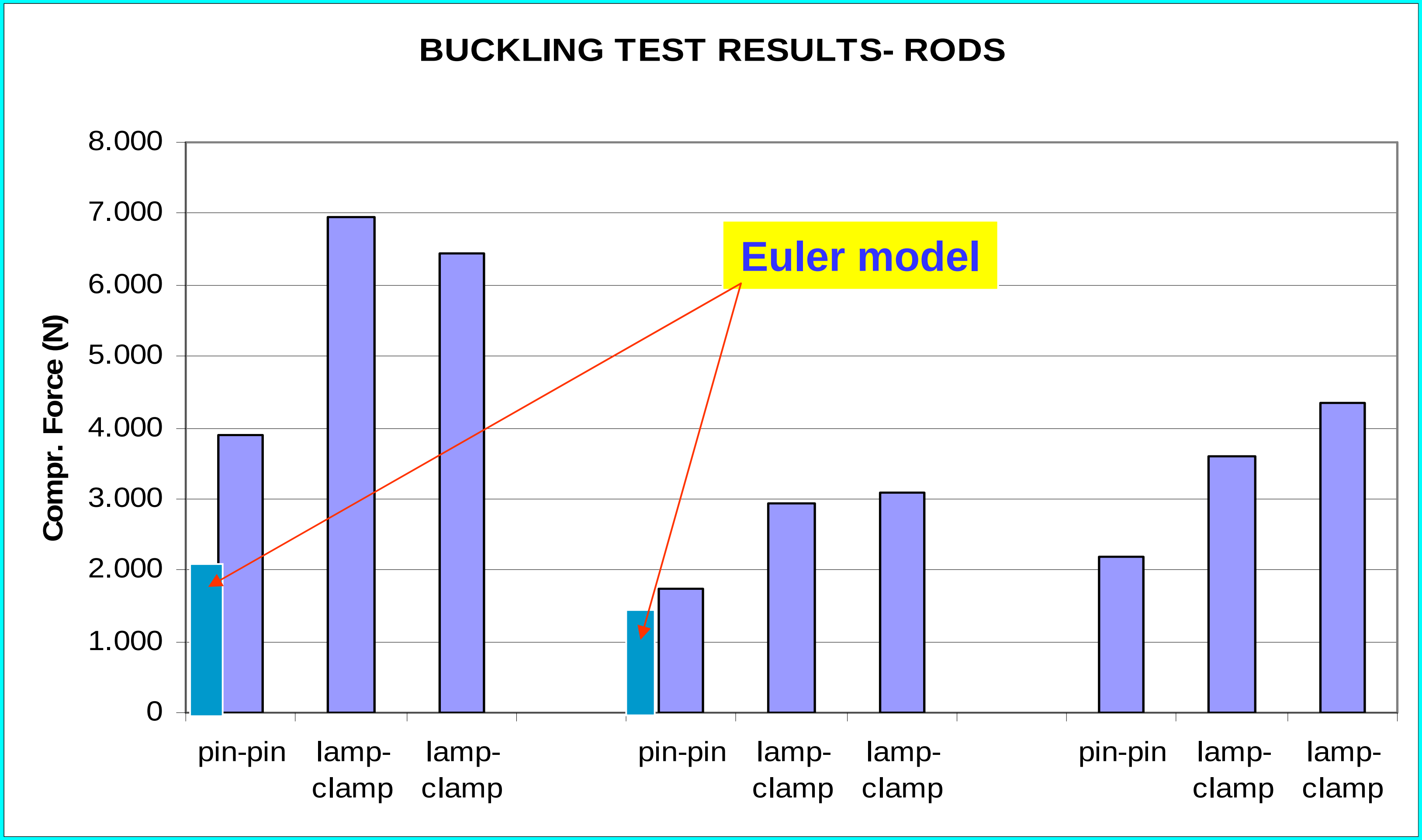
Bi-articulated rod(diam. 6mm) (L= 250 mm)



Bi-Clamped rod (6mm diameter)



Rods with ceramic core –BCE/UPC



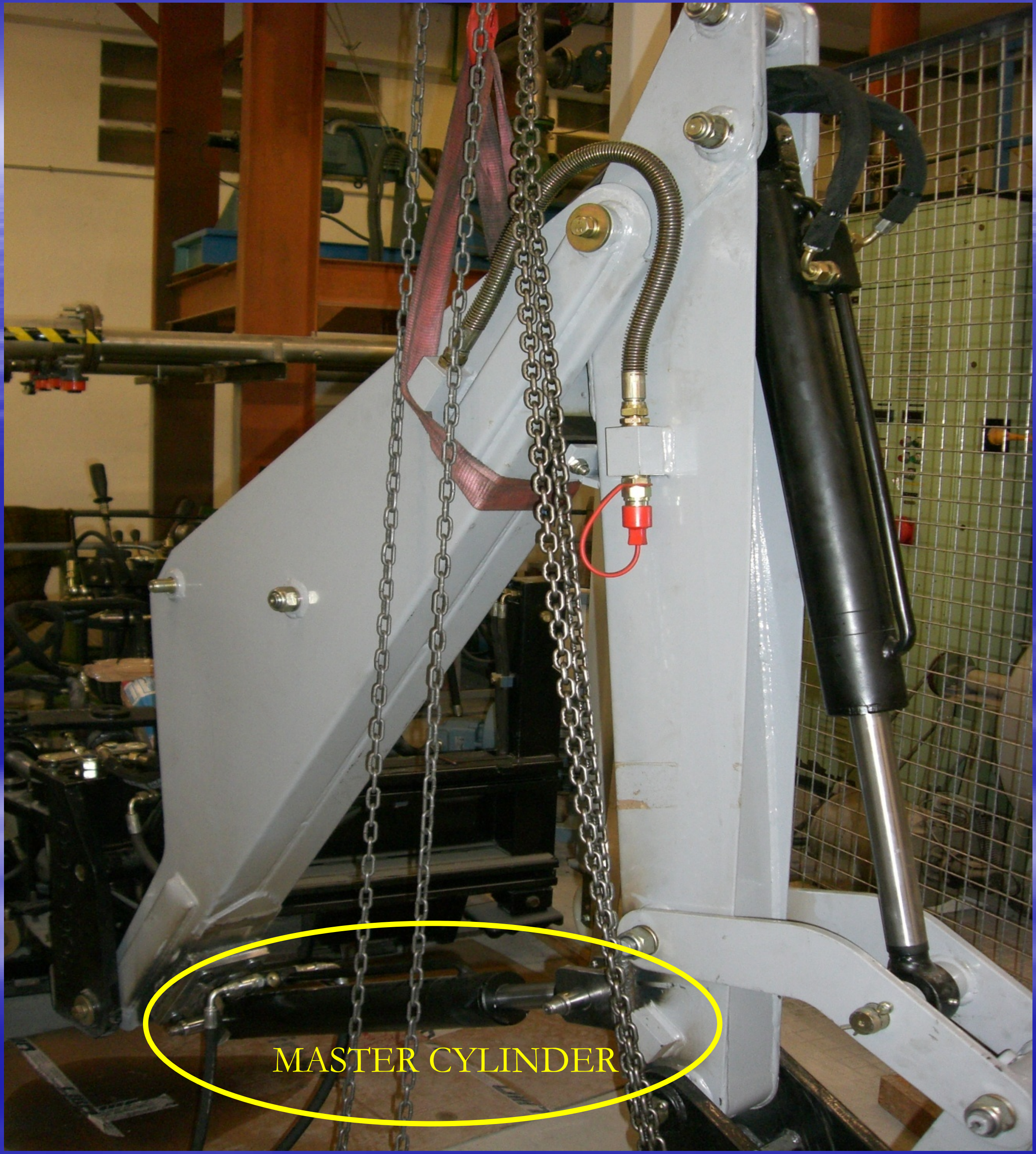
Full section Annular section Annular+Ceramic

FIELD TESTS

- Indoor test with backhoe (HIDRAR/UPC) (cylinders and rods)
- Field test with backhoe (HIDRAR-BMH)

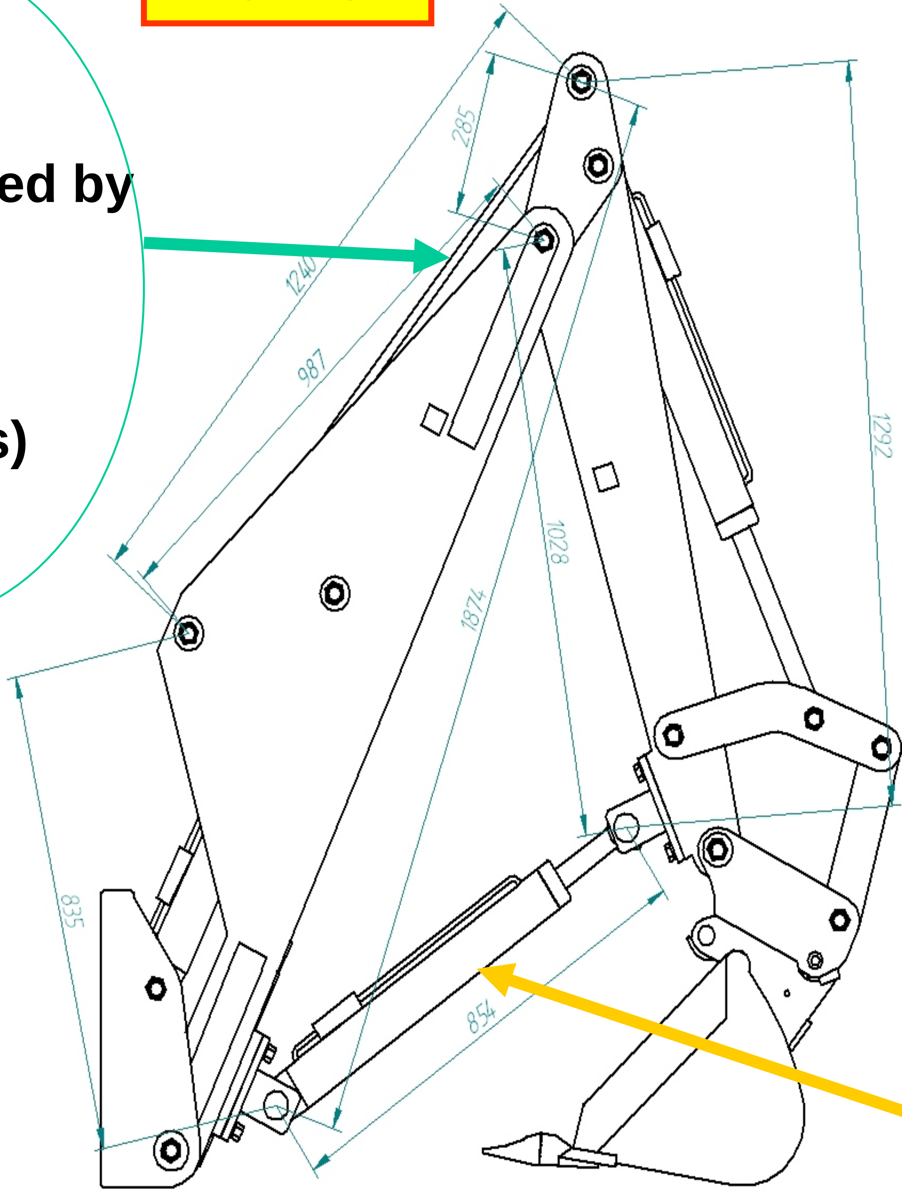
Indoor tests with backhoe (HIDRAR/UPC)
(cylinders and rods)

BACKHOE FRAME


MASTER CYLINDER


BACKHOE

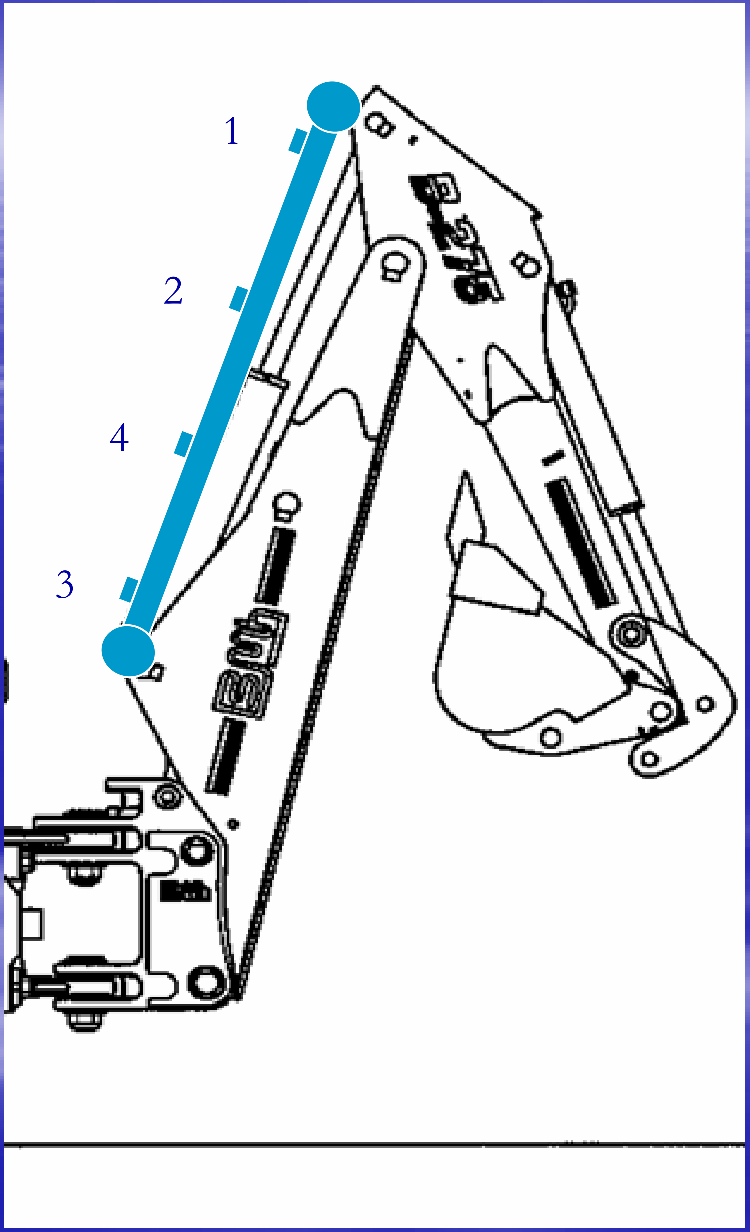
Cylinder substituted by a simple rod(for buckling purposes)

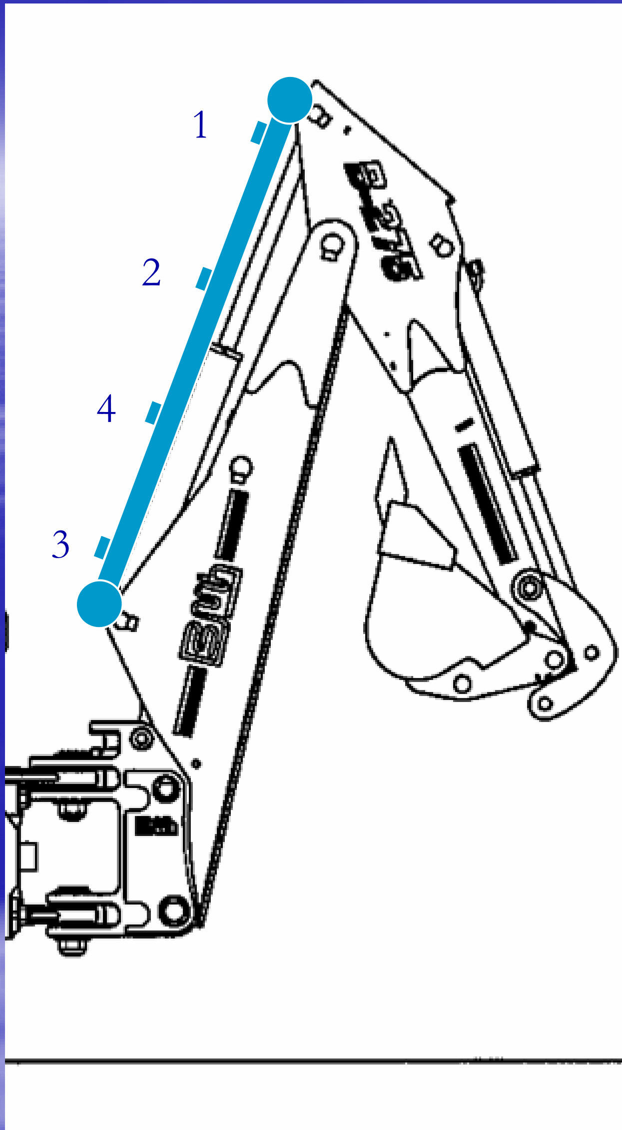


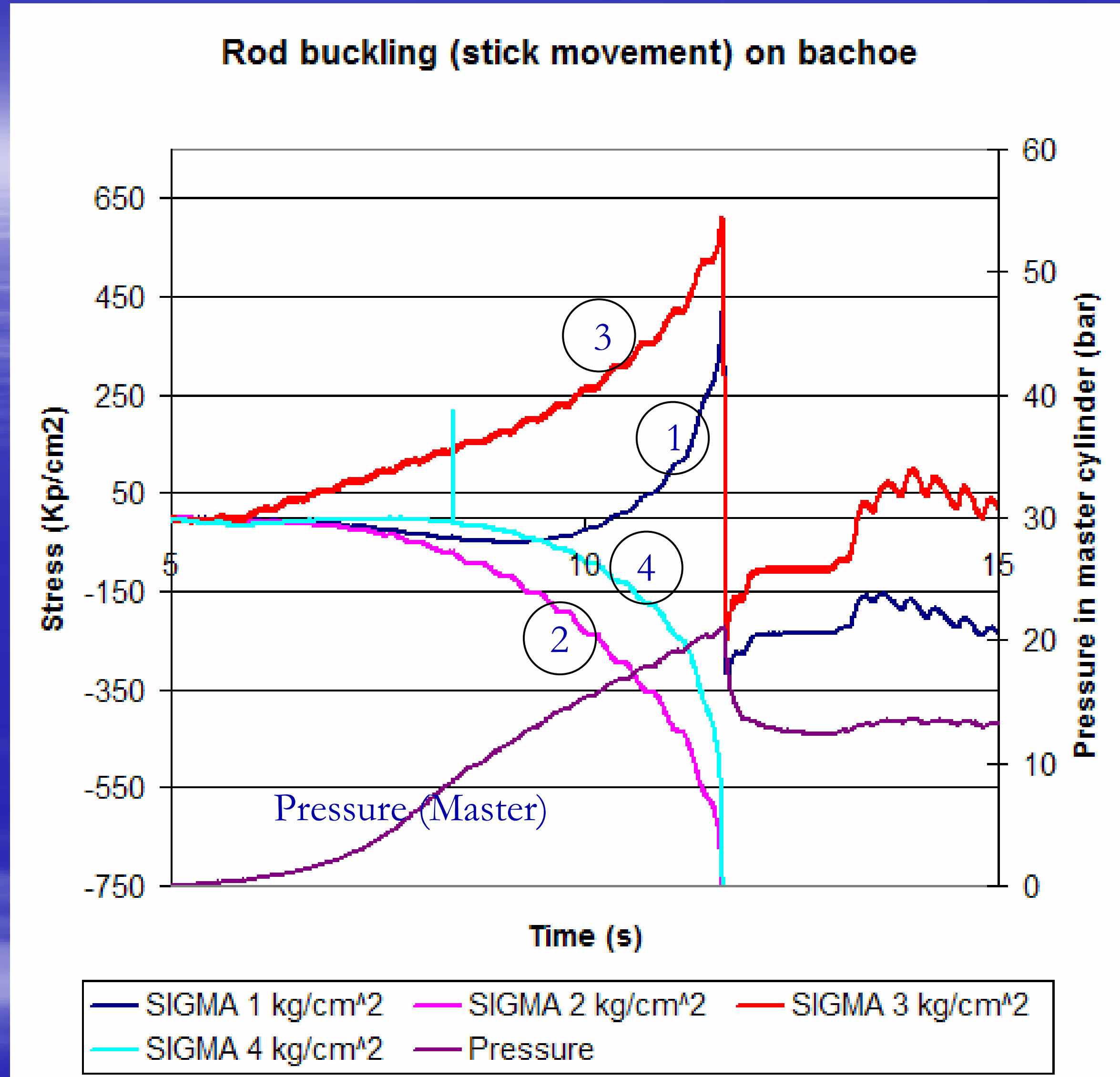
MASTER CYLINDER
Mechanical advantage=8

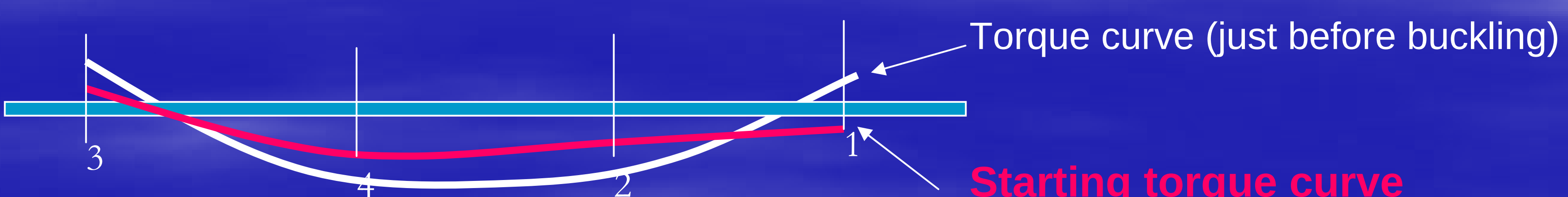
Rod test on backhoe machine

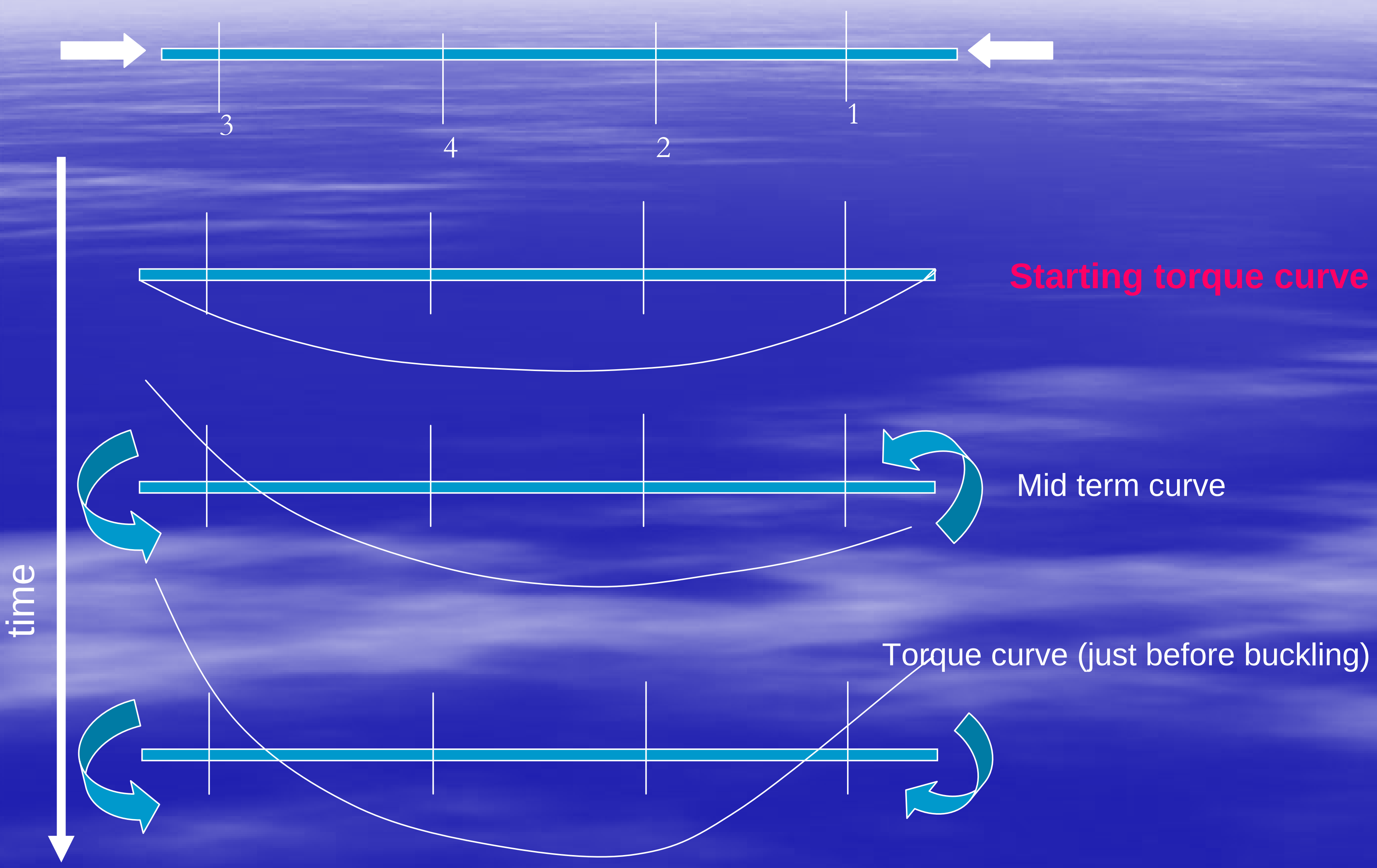
Rod	D ext	D int	L
FULL SECTION	15	0	1.240
	20	0	1.240
	25	0	1.240
	30	0	1.240
ANNULAR SECTION	15	9	1.240
	20	14	1.240
	25	19	1.240
	30	24	1.240


1
2
4
3



1
2
4
3

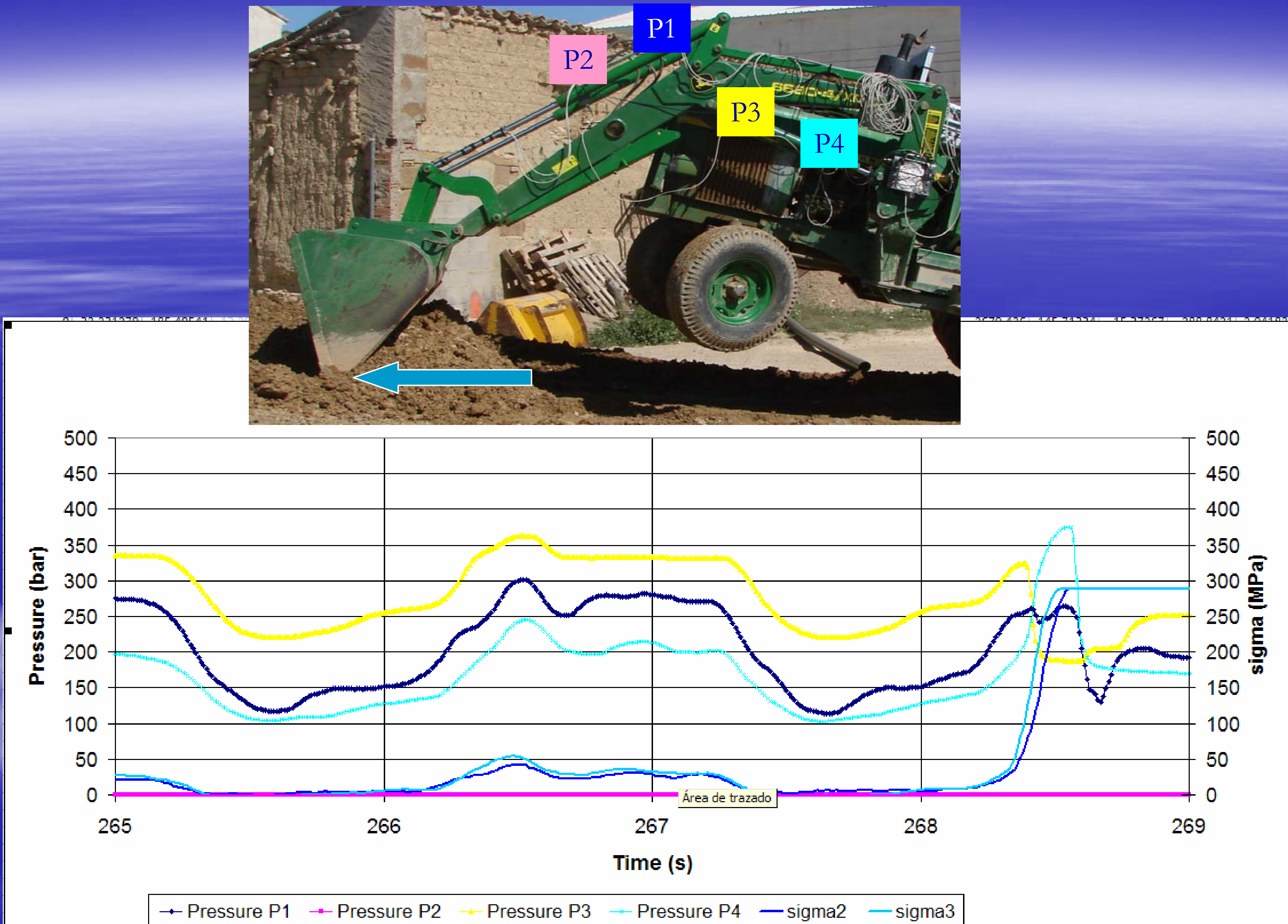

Rod buckling (stick movement) on bachoe
650
450
250
50
-150
-350
-550
-750
60
50
40
30
20
10
0
5
10
15
Stress (Kp/cm2)
Pressure in master cylinder (bar)
Time (s)
3
1
4
2
Pressure (Master)
SIGMA 1 kg/cm^2
SIGMA 2 kg/cm^2
SIGMA 3 kg/cm^2
SIGMA 4 kg/cm^2
Pressure

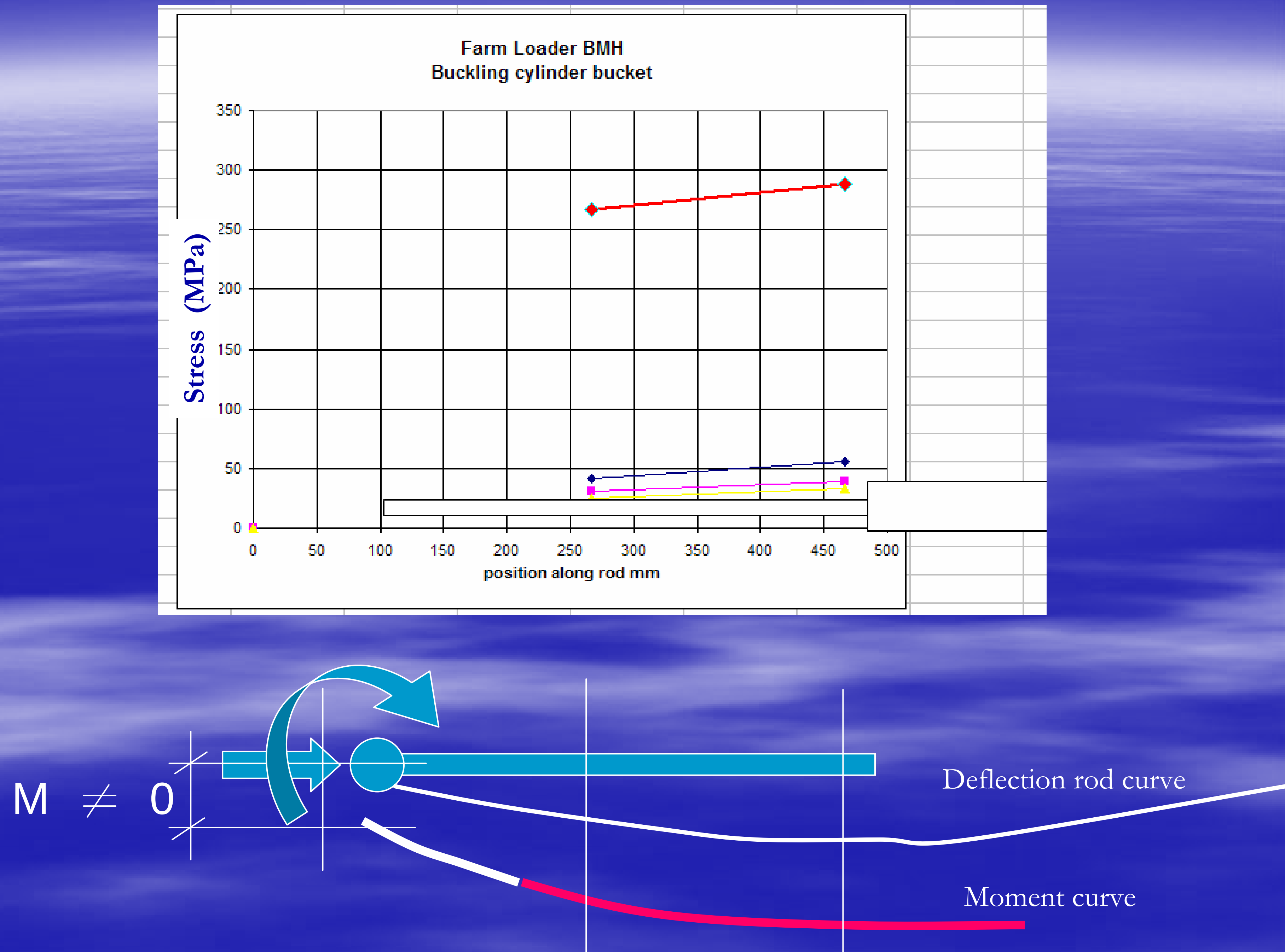

3
4
2
1
Torque curve (just before buckling)
Starting torque curve


3
4
2
1
time
Starting torque curve
Mid term curve
Torque curve (just before buckling)

FARM LOADER


6680-4/XD.II


P1
P2
P3
P4
Pressure (bar)
sigma (MPa)
0 50 100 150 200 250 300 350 400 450 500
265 266 267 268 269
Time (s)
Área de trazado
Pressure P1
Pressure P2
Pressure P3
Pressure P4
sigma2
sigma3



Farm Loader BMH
Buckling cylinder bucket
Stress (MPa)
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
position along rod mm
M ≠ 0
Deflection rod curve
Moment curve

ISO 13.725
Excel sheet application

PARAMETROS DEL ACTUADOR

		Referencia		
CILINDRO	Longitud del cilindro	l1	0,8	m
	Diámetro Exterior	d1_e	0,06	m
	Diámetro interior	d1_i	0,05	m
	Módulo de elasticidad	e1	2,00E+11	Pa
VASTAGO	Longitud que sale el vástago	l2	0,6	m
	Longitud total del vástago	lvas	0,7	m
	diámetro del vástago	d2	0,03	m
	Módulo de elasticidad	e2	2,00E+11	Pa
Datos de diseño	excentricidad de carga	e_off_axis	2	mm
	Tensión de fluencia	sigma_e	3,40E+08	Pa
	factor de seguridad	k	1	

apoyado- apoyado.xls
empotrado - apoyado.xls
apoyado - empotrado.xls
empotrado - empotrado.xls
empotrado - libre.xls
empotrado - libre (empotrado).xls

Calcular

Finalizar

Carga Critica de pandeo: 70,55 kN

Tensión máxima admisible: 339,63 MPa

Carga de Euler: 40,04 kN

Carga máxima admisible: 55,8 KN

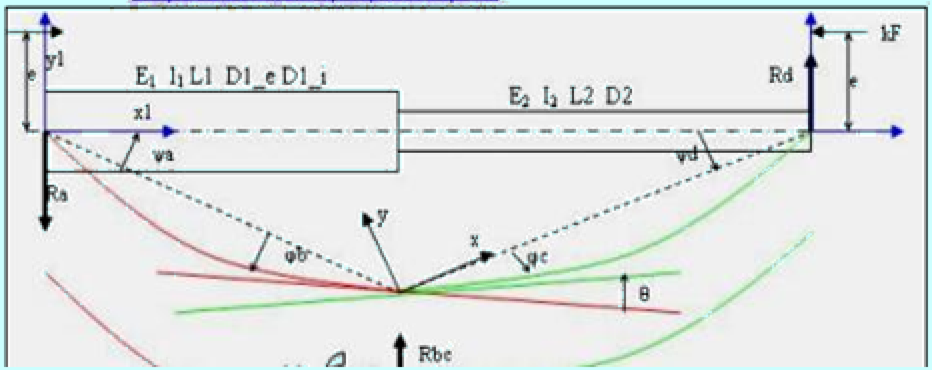
Tensión a comp simple: 78,93 MPa

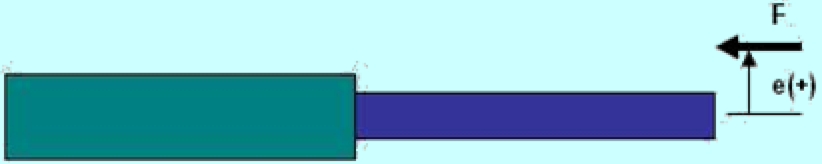
Tipos de montaje:

- (•) apoyado - apoyado
- ( ) empotrado - apoyado
- ( ) apoyado - empotrado
- ( ) empotrado -empotrado
- ( ) empotrado - libre
- ( ) empotrado - libre(emp)

PARAMETROS a Fmax admisible

Ra	-44,684	N
Rbc	-8,148	N
Rd	40,567	N
Ma		N m
Md		N m
Mbc	-678,455	N m
teta	0,16294	grados
psi_a	0,70887	grados
psi_d	0,94516	grados
phi_a	0,00000	grados
phi_b	0,17846	grados
phi_c	-1,31263	grados
phi_d	0,00000	grados





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 13725Excel 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.