Development of BRD_Al Prototype

Development of aluminium alloy hysteretic damping system for seismic retrofitting of pre-code reinforced concrete buildings

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Development of BRD_Al Prototype

Presentation outline

Introduction:

- The problem
- Objectives

Developments:

- Information about the available aluminium alloys, its production and processing;
- Definition of the aluminium alloys targeted for the development of the BRD_AL prototype;
- Numeric analyses performed with different confirgurations of the dissipative device;

Future work

State of the Art – Dissipative devices – Brief overview

<table>
<tr><th colspan="3">Classification of devices</th></tr>
<tr><td rowspan="3">Displacement Dependent</td><td colspan="2">Linear(LD)</td></tr>
<tr><td rowspan="2">Non-Linear (NLD)/Hysteretic(HD)</td><td>Yielding metal (YMD)</td></tr>
<tr><td>Friction (FD)</td></tr>
<tr><td rowspan="2">Velocity Dependent/Viscous Dampers (VD)</td><td colspan="2">Fluid Viscous (FVD)</td></tr>
<tr><td colspan="2">Fluid Spring (FSD)</td></tr>
<tr><td colspan="3">Acceleration dependent</td></tr>
<tr><td colspan="3">Modified Input</td></tr>
<tr><td colspan="3">Combination</td></tr>
</table>

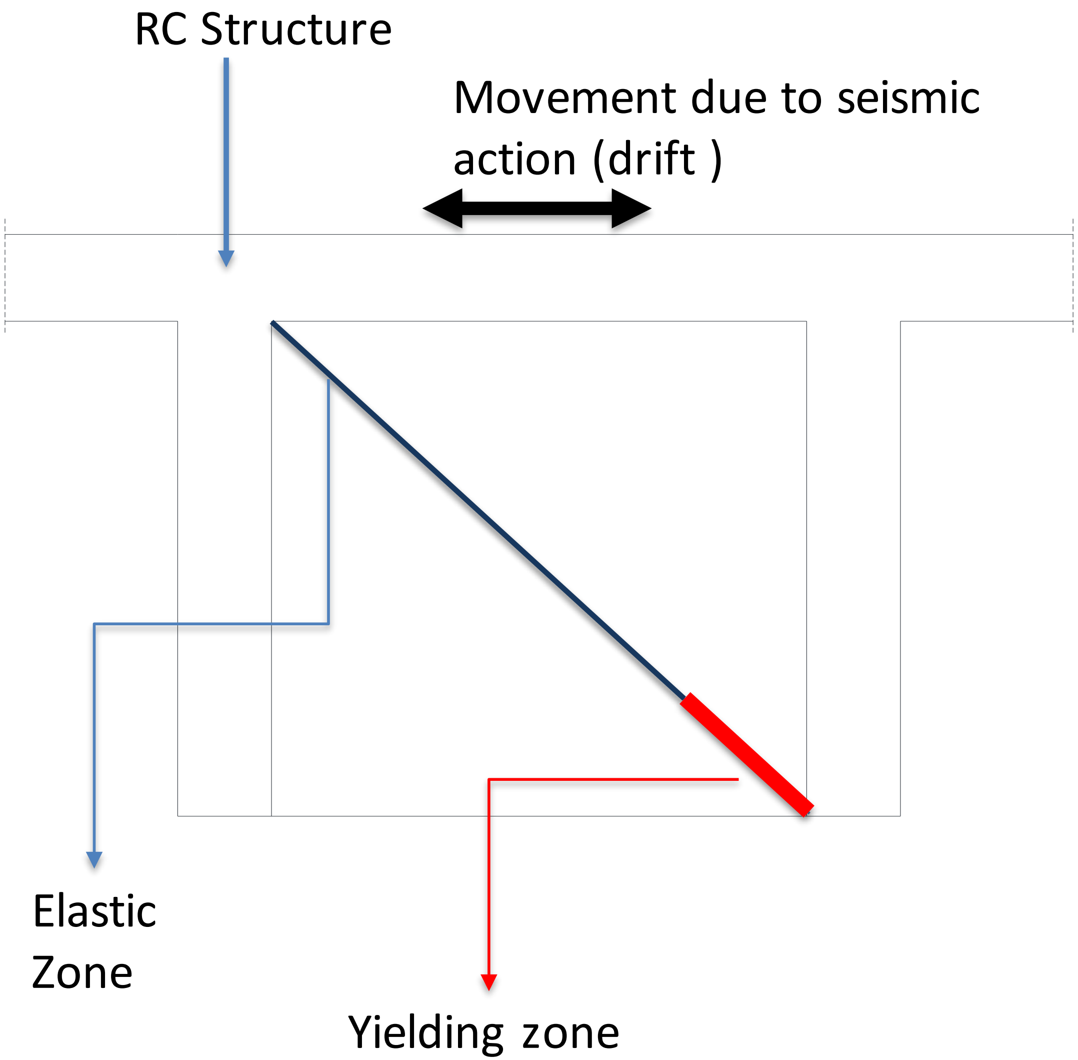
Source : Frederico Mazzolani, Luis Calado, Chapter 1 - *Introduction to reversible mixed technologies, Earthquake Protection of historical buildings by reversed mixed technologies, Vol.2 - FP6 PROHITECH project*

Hysteretic behaviour of Buckling Restrained Braces- as a principle for the development of new device

Development BRD_Al Prototype

Objectives:

- Alternative to the dissipative bracing device paradigm: use an extruded aluminium alloy member without infill;
- Develop a cross-section to prevent buckling of both core and casing ;
- Light-weight and easy to integrate in bracing system;
- Device that is simple to integrate both in new and existing buildings
- Capable of withstanding significant plasticization, hence increasing structural damping due to hysteretic behaviour of the aluminium member;



Development BRD_Al Prototype

Definition of the aluminium alloy

Aluminium alloy designation system	
Wrought alloys	Series
	1xxx
Alloys grouped in major alloying elements	
Cu	2xxx
Mn	3xxx
Si	4xxx
Mg	5xxx
Mg and Si	6xxx
Zn	7xxx
Other elements	8xxx
Unused series	9xxx

Aluminium alloy designation system	
Cast alloys	Series
	1xx.x
Alloys grouped in major alloying elements	
Cu	2xx.x
Si+Cu or Mg	3xx.x
Si	4xx.x
Mg	5xx.x
Zn	6xx.x
Sn	7xx.x
Other elements	8xx.x
Unused series	9xx.x

Wrought alloys: The alloys groups is defined by the first digit. Modifications of the original alloy and impurity are indicated by the second digit. In the case of the group 1xxx, the last two digits the % of aluminium above 99%.
For alloys of groups 2xxx to 8xxx, the last two digits serve to further identify individual aluminium alloys

Cast alloys: First digits indicates the major alloying group. The following second digits indicate the aluminium purity. The digit to the right indicates the product form either casting or ingot

First number indicates the number of series. The second is mainly 0 and can vary from 1 to 9 for its modifications. The third and fourth figure identifies the specific alloy within the group

Development BRD_Al Prototype

Aluminium alloy – Fabrication stage designations

Rough stage of fabrication (**F**)	Work hardened products, without control of cold working rate nor its thermal conditions
Annealed stage (**O**)	Annealed products to obtain lower strength temper or to improve ductility
Work-hardened stage (**H**)	Products whose strength has been increased by cold working, with or without thermal treatments.
Tempered non-stabilized stage (**W**)	Products subjected to solution treatment, with uncontrolled temper and then aged at room temperature;
Heat-treated stage (**T**)	Products that have been treated by a predefined combination of processes such as: Solution Tempering Natural or artificial ageing Quenching

Development BRD_AL Prototype

Definition of the aluminium alloy

Heat treatment stage possibilities:

Basic treatments (sequence)				Designation
Heat treatment with solution treatment	Without work hardening	Naturally aged		T4
Heat treatment with solution treatment	Without work hardening	Artificially aged		T6
Heat treatment with solution treatment	With work hardening	Work hardened	Naturally aged	T3
Heat treatment with solution treatment	With work hardening	Work hardened	Artificially aged	T8
Heat treatment with solution treatment	With work hardening	Artificially aged	Work hardened	T9
Heat treatment without solution treatment	Without work hardening	Naturally aged		T1
Heat treatment without solution treatment	Without work hardening	Artificially aged		T5
Heat treatment without solution treatment	With work hardening	Work hardened	Naturally aged	T11
Heat treatment without solution treatment	With work hardening	Work hardened	Artificially aged	T12
Heat treatment without solution treatment	With work hardening	Artificially aged	Work hardened	T10

Temperature and time of ageing play an important role in the definition of the alloys mechanical behaviour

Development BRD_Al Prototype

Definition of the aluminium alloy

EN AW 6082-T6 (initial state)

Chemical composition (% of weight)									
Elements :	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Max	0,7	-	-	0,4	0,6	-	-	-	-
Min	1,3	0,5	0,1	1	1,2	0,25	0,2	0,1	rest

- Mg and Si are the main alloying elements;
- Mechanical properties can be enhanced by thermal treatments;
- Good corrosion resistance

EN AW 5083 –H111 (initial and final state)

Chemical composition (% of weight)									
Elements :	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Max	-	-	-	0,4	4	0,05	-	-	-
Min	0,4	0,4	0,1	1	4,9	0,25	0,2	0,15	rest

- Alloys that cannot be heat treated;
- Higher mechanical properties than of those of 2xxx, 3xxx, 4xxx;
- High corrosion resistance, when Mg % is less than 6%;

Development BRD_Al Prototype

Definition of the aluminium alloy

Studied alloys

→ EN AW 6082-T6 (initial state) → Heat treatable alloy

→ EN AW 5083 –H111 (initial and final state) → Non heat treatable alloy

<u>Choice criteria:</u>

- Expert opinion;
- Availability;
- Price;
- Mechanical behaviour;
- Corrosion resistance

Characterization of aluminium alloys

Characterization of the mechanical behaviour of the 6082-T6 and 5083-H111 alloys

Uniaxial tension tests

Plate specimens

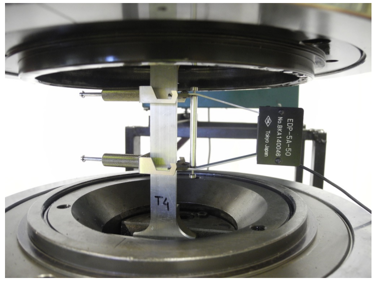
Uniaxial cyclic tests

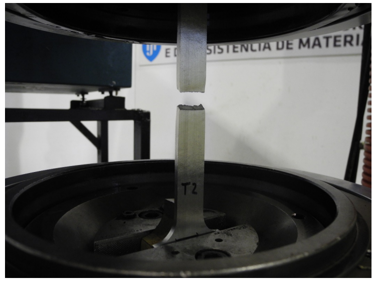
Rod type specimens (AW 6082-T6);
Squared bars (AW 5083 –H111)

Objectives:

- Assess the mechanical behaviour of the alloys, especially when subjected to cyclic loading;
- Determine the best suited alloy to be used in BRD_AL production;
- Dissemination of experimental results of tested aluminium alloys

Uniaxial tension tests results:





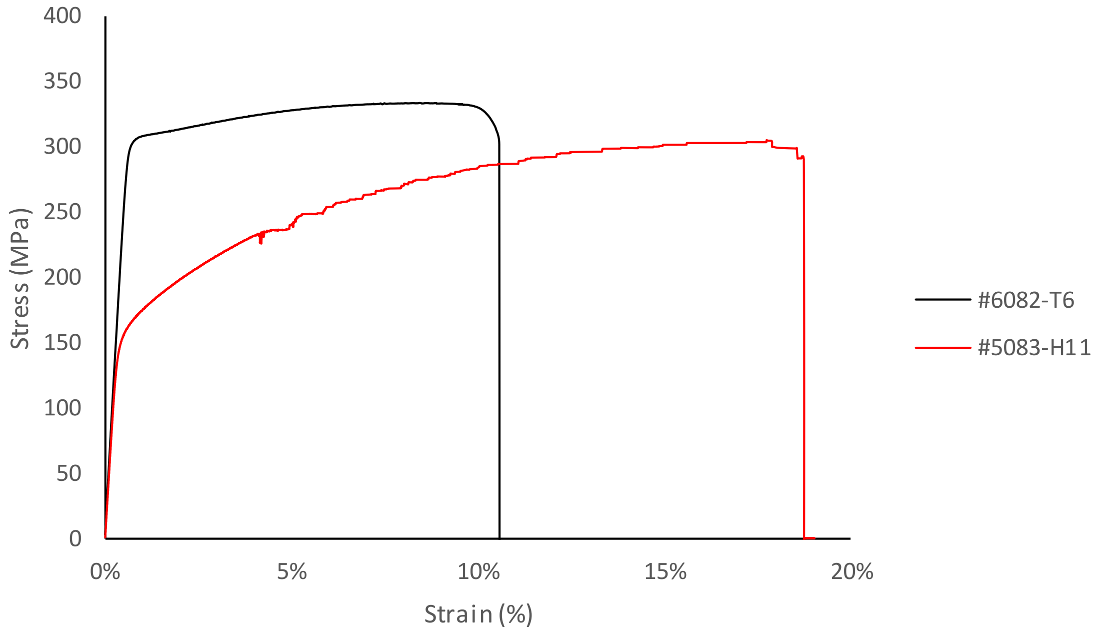
i. Tested alloys present quite different hardening rate (this rate quite low in case of the 6082-T6 alloy).

ii. Alloys show different with respect to yield and ultimate strengths. The 6082-T6 yield stress ($f_{y,}$ =290 MPa) is approx. doubles the 5083-H111 yield strength. However, ultimate strength of 6082-T6 (f_{ult}=333 MPa) is only 9% higher than 5083-H111 (f_{ult}=305MPa).

iii. Alloys also show differences with regard to plastic strain . 5083-HH111 show much higher strain capacity. The ultimate strain (ε_u) of 6082-T6 is almost 50% lower than the 5083-H111 ε_u

iv. For both alloys, similar elastic behaviour was observed. The young modulus in tension attained for both cases is approx. E= 70 GPa.

v. Regarding damage evolution, it possible to observe that rupture occurs right after damage initiation, indicating a brittle damage controlled (possibly) by the material ultimate shear strain (to be analysed more thoroughly)



Characterization of aluminium alloys

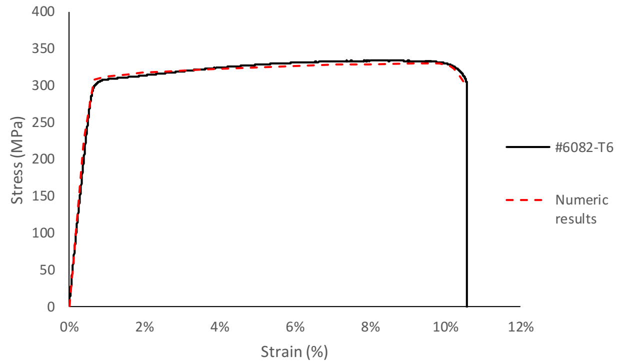
Uniaxial tension tests – Numeric analysis

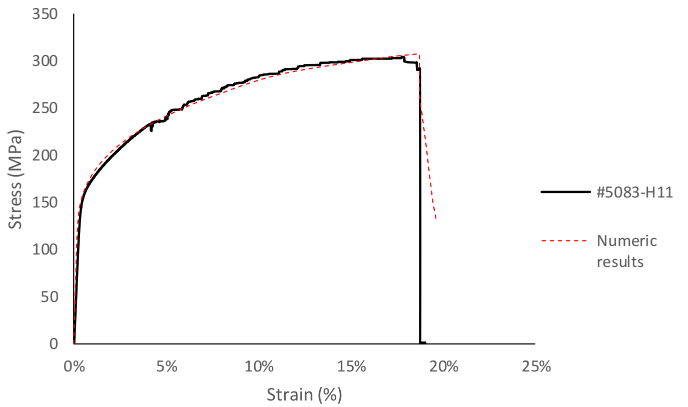
Numeric modelling of uniaxial tension behaviour
Inelastic behaviour of metal - Johnson Cook plasticity model, using ABAQUS software

Hardening law:

$$\sigma^0 = \left[A + B\left(\bar{\varepsilon}_{pl}\right)^n\right]\times\left(1-\hat{\theta}^m\right)$$

- A, B, n, m material parameters obtained from test results;
- $\hat{\theta}$ is a non dimensional temperature that for values of exposition below the transition temperature is equal to 0;
- Element type: C3D8R – 8 node linear brick, reduced integration and hourglass control





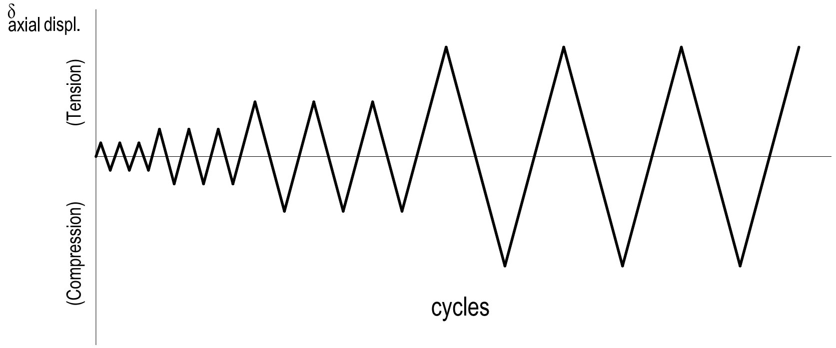
Test specimen	γ (t/m³)	E (Gpa)	A (Mpa)	B	n
#6082-T6 - Numeric	2,7e-3	65	290	310	0,75
#5083-H111 - Numeric	2,7e-3	70	110	390	0,32

Ductile damage initiation - Parameters				Ductile damage evolution - Parameters		
Test specimen	ε_{fract} (mm)	σ_{triax} (mm)	ε_{rate}	$\delta_{failure}$ (mm)	Softening	Exp n
#6082-T6 - Numeric	0,15	0,57	0,001	13	exponential	10
#5083-H111 - Numeric	0,12	0,57	0,001	7,5	exponential	2

Shear damage initiation - Parameters				Shear damage evolution - Parameters		
Test specimen	ε_{fract} (mm)	σ_{triax} (mm)	ε_{rate} (mm)	$\delta_{failure}$ (mm)	Softening	Exp n
#6082-T6 - Numeric	0,1	0,57	0,001	13	exponential	10
#5083-H111 - Numeric	0,2	0,57	0,001	16	exponential	22

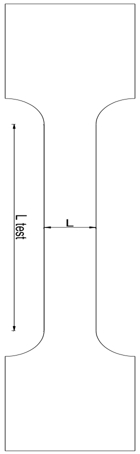
Experimental campaign - Cyclic behaviour of alloys

Imposition of deformations with increasing amplitude; starting with a predetermined yield displacement for the alloy.



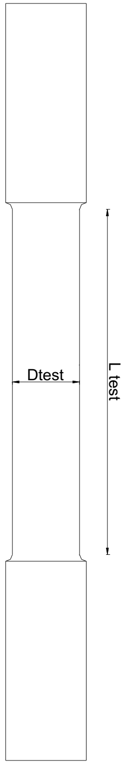
Loading history

5083 –H111 alloy test specimens



Test specimen	L (mm)	L test (mm)	A test (mm²)	λ_G
5083_CL	20	66	491	3

6082–T6 alloy test specimens



Test specimen	Dtest (mm)	Ltest (mm)	Atest (mm)	λ_G
C1	25	100	491	4
C2	25	125	491	5
C3	25	160	491	6
C4	25	179	491	7
C5	25	250	491	10
C6	25	300	491	12

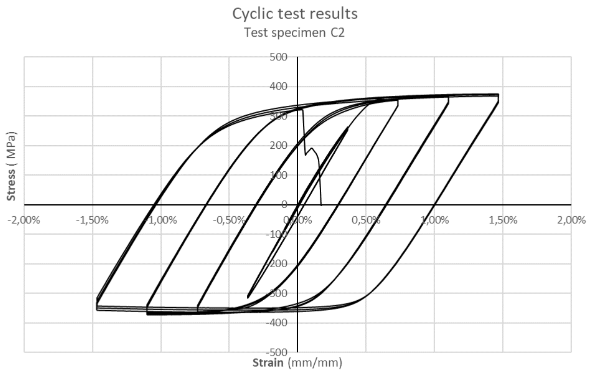
Aluminium Alloy analyses

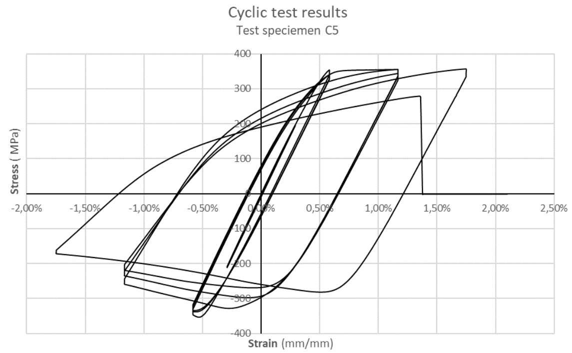
Experimental campaign - Cyclic behaviour of the 6082 –T6 – Results (resume)

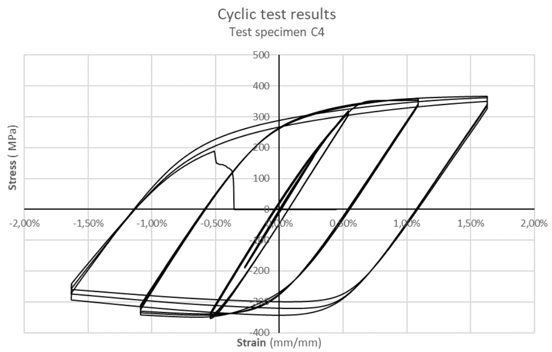
Test specimem C2 (λ_G=5) diagram show rather stable cycles until rupture, no visible effect of slenderness;

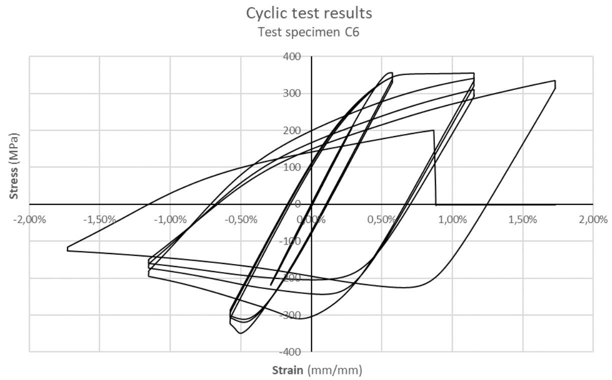
Test specimen C4, λ_G=7,19, the effect of slenderness is negligible in first cycles in plastic regime, although becomes evident in the final cycles before rupture. cycles remain rather stable until rupture. Loss of strength occurs mainly in the last cycles, more predominantly in the last half cycles in compressions;

In test specimens C5 (λ_G=10) and C6 (λ_G=12) , the influence of slenderness (negative tendency of the half cycles in compression) becomes evident right at the first cycles in the plastic regime. Diagrams show pronounced decay in strength during plastic regime, both in tension and compression. This strength decay is progressive until rupture.







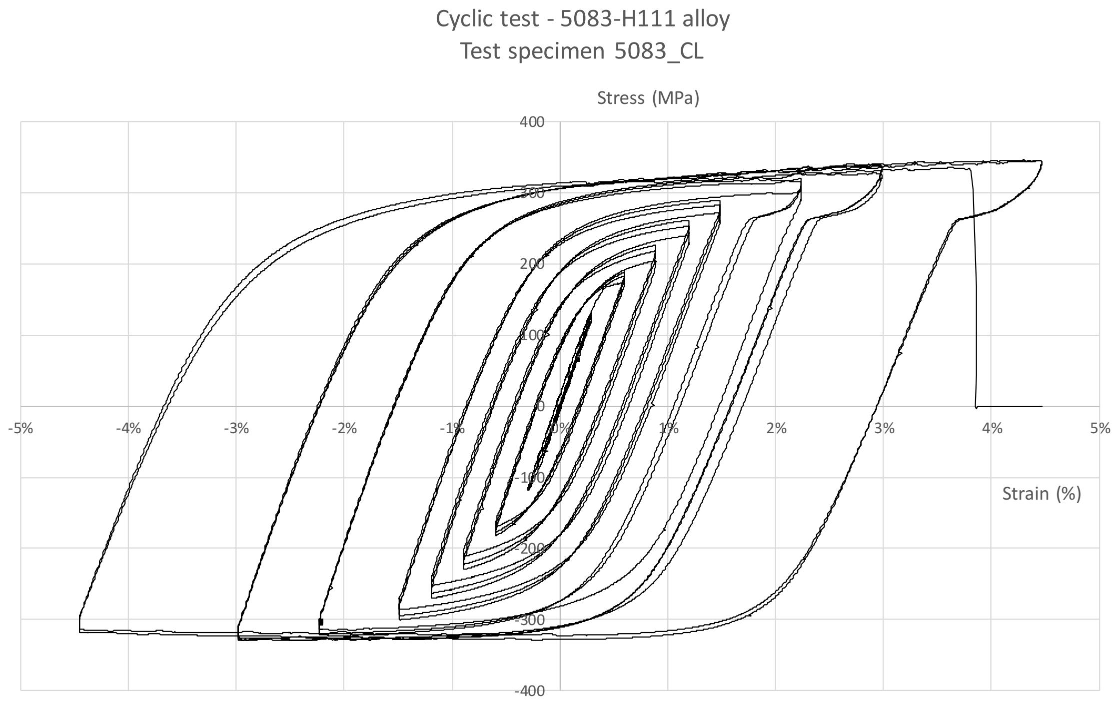


- In all tested cases, the values achieved for the maximum plastic strain were quite small (around 1,5 %)

Aluminium Alloy analyses

Experimental campaign - Cyclic behaviour of the 5083-H111 alloy (Preliminary)

- High symmetry. Strength decay occurs abruptly only at rupture of the test specimen;
- Maximum strength before rupture is similar to the one achieved with the 6082-T6 alloy;
- Combined isotropic/kinematic hardening occurs in almost all cycles except in the last cycle before rupture;
- Tension semi-cycles, both in tension and in compression, show only some decay in the last set cycle, mainly in the half-cycles in compression;
- Test specimen shows rather stable cycles until rupture;
- Maximum plastic strain is almost triple of the maximum plastic strain of 6082-T6 alloy.
- More cyclic tests of the 5083-H111 will be carried out



Numeric modelling of cyclic behaviour both alloys- Combined isotropic/kinematic non linear (Lemaitre and Chaboche - defined in ABAQUS software)

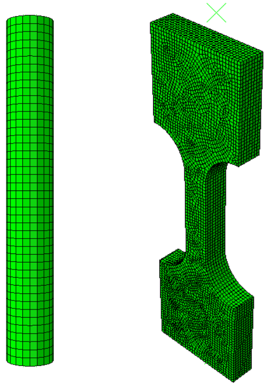
- Isotropic hardening : $\sigma^0 = \sigma|_0 + Q_\infty\left(1 - e^{-b\bar{\varepsilon}^{pl}}\right)$

- Kinematic hardening (evolution of back-stress α_k in a stable cycle – simplified expression for calibration purposes

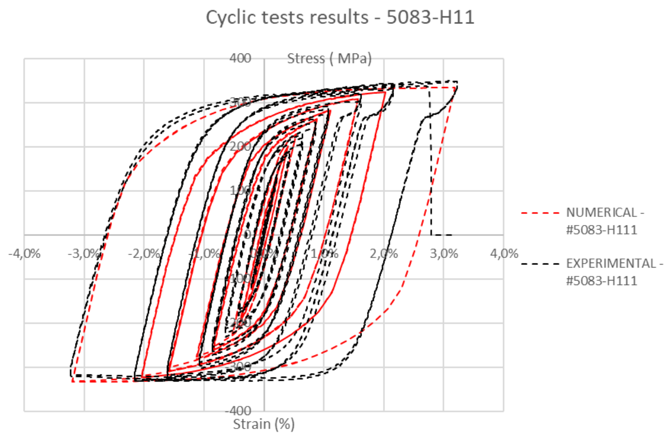
$$\alpha_k = \frac{C_k}{\gamma_k}\left(1 - e^{-\gamma_k \varepsilon^{pl}}\right) + \alpha_{k,1} e^{-\gamma_k \varepsilon^{pl}},$$

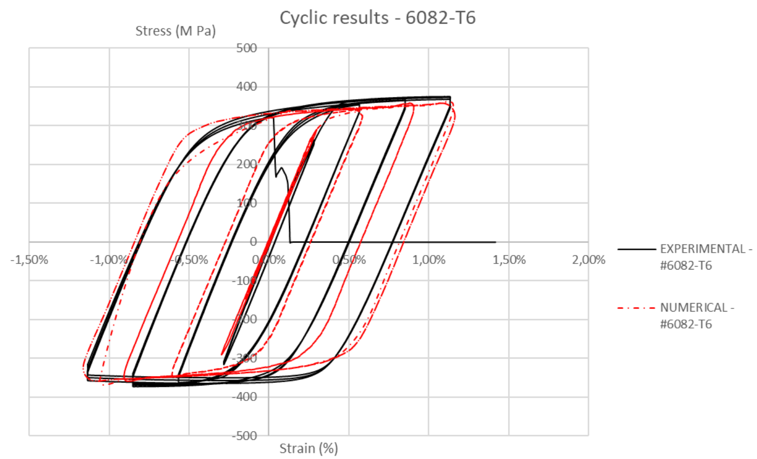
Overall back stress $\alpha = \sum \alpha_k$

Above expressions used calibrate to calibrate C_k and γ_k



element type: C3D8R



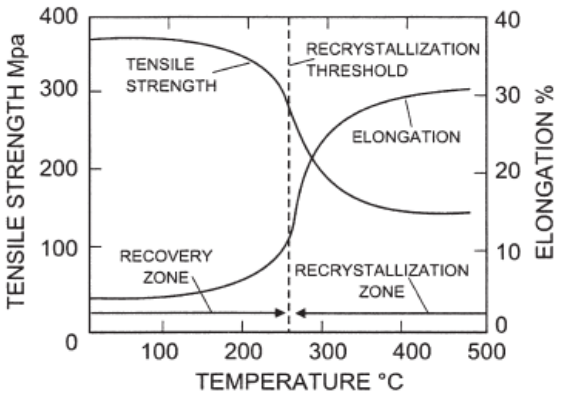


Parameters for plastic cyclic behaviour											
Material	$\sigma\|_0$	Q_∞	b	C_1	γ_1	C_2	γ_2	C_3	γ_3	C_4	γ_4
6082-T6	290	-	-	65000	2500	25000	800	15000	250	1500	25
5083-H111	110	15	3,45	100000	1000	5000	50	250	25	-	-

Aluminium Alloy - Thermal treatments

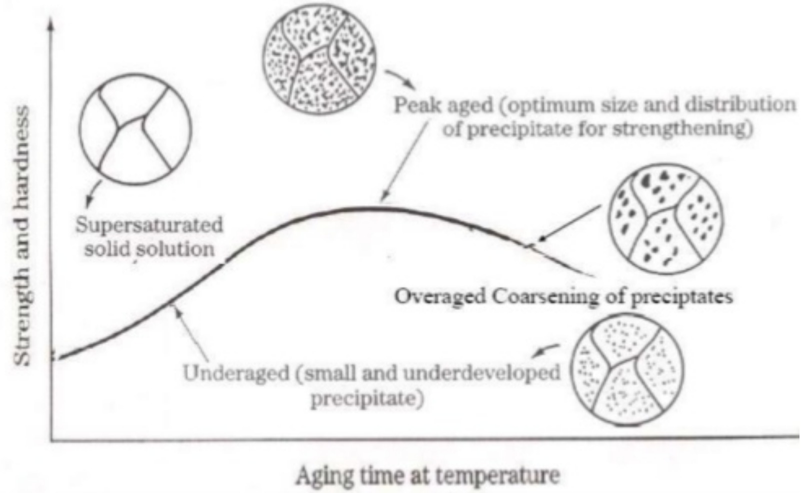
Thermal treatment of alloy 6082

- Great improvements in the mechanical properties of these alloys can be achieved by suitable solution treatment and ageing operations;
- Transformations phases are induced by changing the temperature of an alloy that as a fixed bulk composition.



Ian Polmear – Light Alloys – From traditional Alloys to Nanocrystals – 4th Edition - Elsevier

Typical precipitation transformations



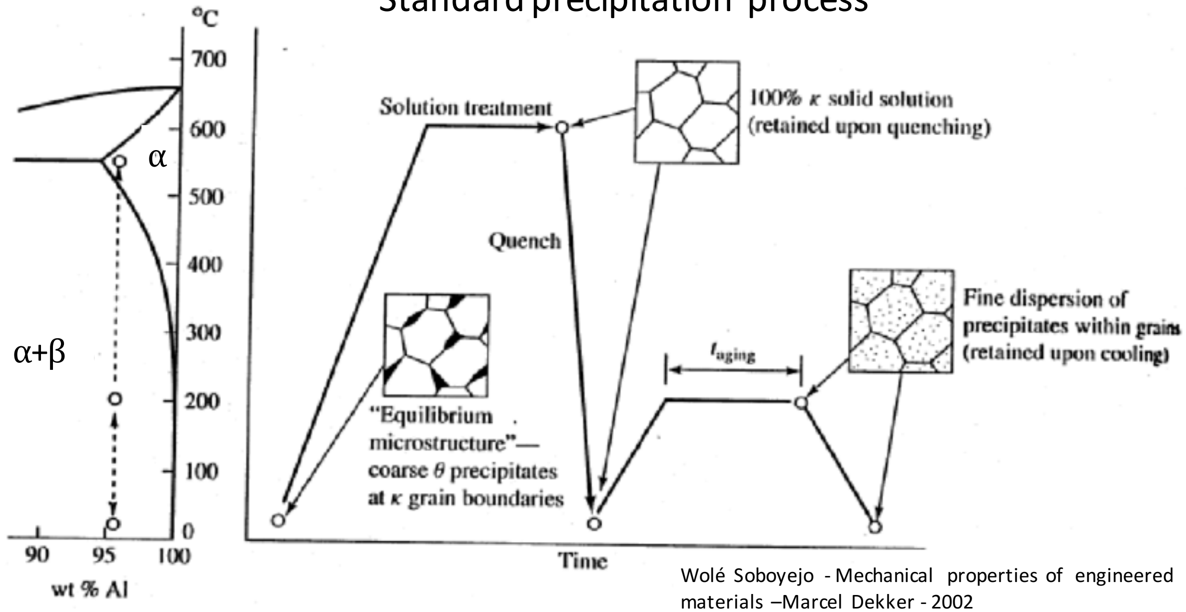
W. F. Smith, Foundations of Material Science and Engineering, McGraw-Hill , 2009

Thermal treatments of the 6082 alloy

Thermal treatment stages:

- Solution treatment;
- Quenching;
- Artificial ageing

Standard precipitation process



Wolé Soboyejo - Mechanical properties of engineered materials –Marcel Dekker - 2002

Precipitation transformations can be expressed by

α → α+β

Metastable super saturated solution

More stable with he same crystal structure as α solid solution

Stable or metastable precipitate

Proposed thermal treatments for the 6082 alloy:

1. Solution treatment at 535ºC (45 min)+ageing at 190 ºC (2h);
2. Solution treatment at 535ºC (45 min)+ageing at 100 ºC (2h);
3. No solution treatment +ageing at 350 ºC (2h)
4. No solution treatment + ageing at 280 ºC (8h)

Change precipitates size, shape and distribution
Change grain dimension

→ Enhance strength and ductility

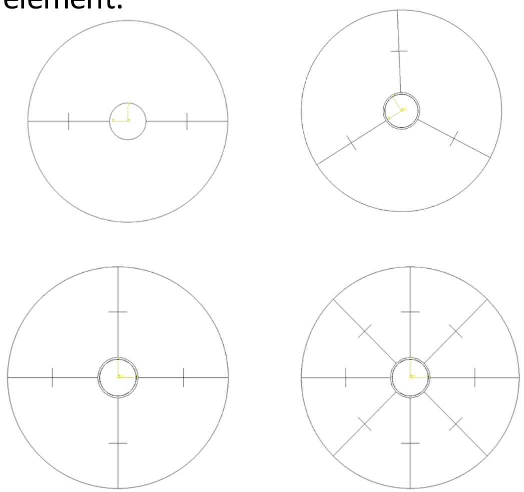
Work in progress

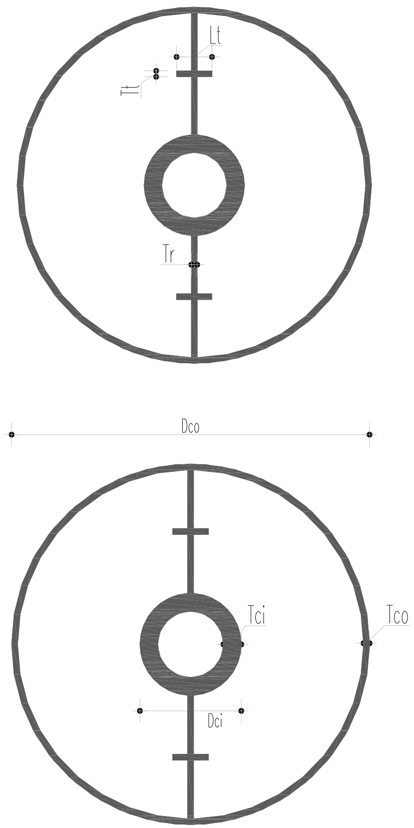
Dissipative element

Numeric analyses for different configuration of the dissipative element

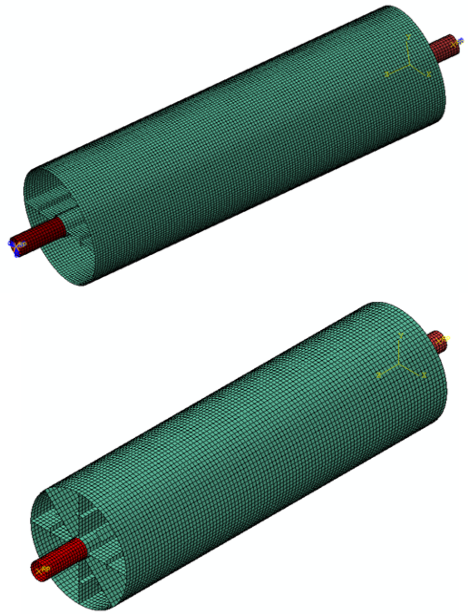
- Material parameters: 6082-T6;
- Loading history: same loading history considered in the cyclic tests

Potential cross section configurations for the dissipative element:





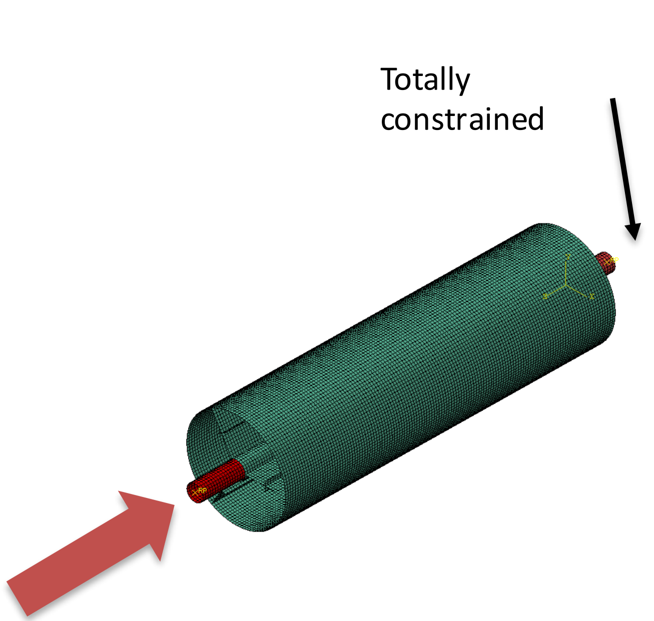
Numeric models (software ABAQUS):



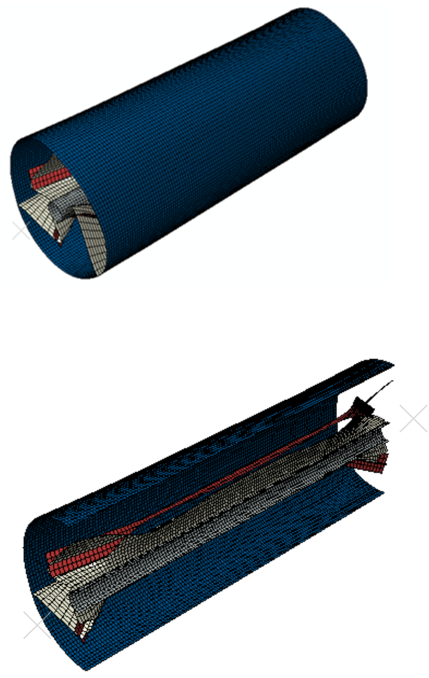
Dissipative element

Numeric analyses for different configuration of the dissipative element

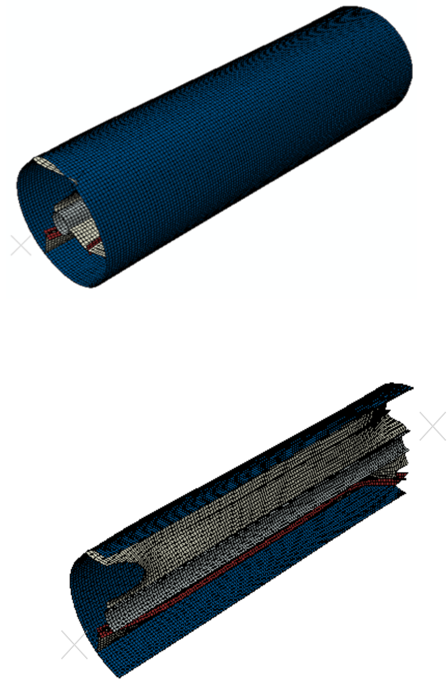
- Buckling analyses for all configurations – Maximum buckling loads of the first 2 modes (preliminary);



D_{co} (mm)	D_{ci} (mm)	T_{co} (mm)	T_{ci} (mm)	T_r (mm)	L_t (mm)	T_t (mm)
120	34	2	6	2	12	2



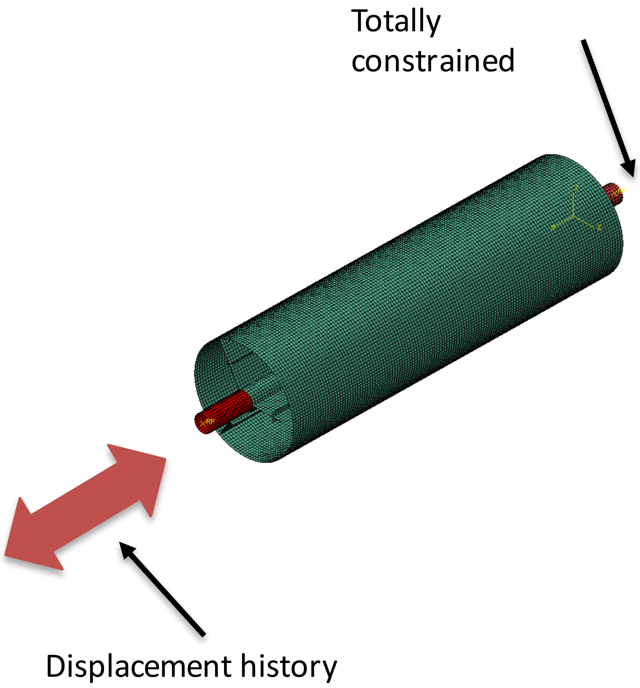
Mode 1-F_{buck} = 1750 kN



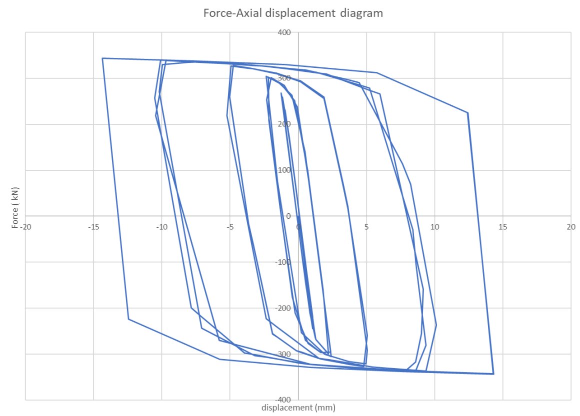
Mode 2-F_{buck} = 2300 kN

Dissipative element

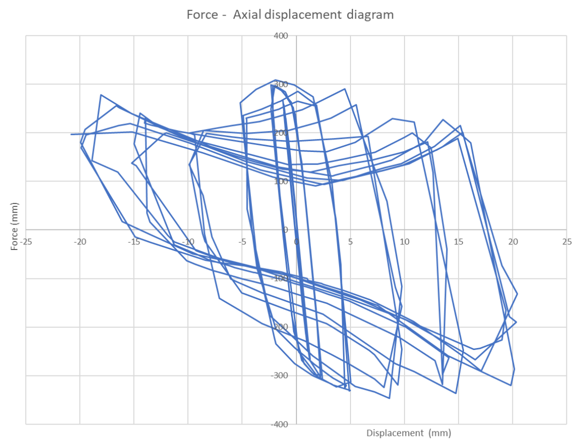
- Buckling displacement field (first 2 modes) used as reference for potential geometric imperfections in dissipative device



Without geometric imperfections



With geometric imperfections (1% mode 1 and 0.5 % mode 2)



Work in progress :

- Enhancing of 6082 alloy ductility - Finalizing the application of heat treatments, to determine which is the most efficient treatment in increasing ductility of the 6082 alloy;

- Mechanical characterization of 6082 alloy, subjected to the proposed heat treatments;

- Choose the most adequate alloy for the BRD_AL prototype;

- Finalize the numerical analysis of potential configurations of the BRD_AL, assessing dissipative capacity of the different configurations

- Numerical analysis of case study building, assessing the effect of non-linear behaviour to cyclic loading in the dynamic behaviour of the building

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EN 10002-1 – "Tensile testing -Part 1: Method of test at ambient temperature;

EN 15129 - "Anti-seismic devices";

ATC 24 - "Guidelines for the cyclic seismic testing of components of steel structures";

ECCS TGW 1.3 1985 - "Recommended testing procedure for assessing the behaviour of structural steel elements under cyclic loads;

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World Aluminium- http://www.world-aluminium.org/publications/
European Aluminium - https://www.european-aluminium.eu

Thank you for your attention.