Development of BRD_Al Prototype

Development of aluminium alloy hysteretic damping system : Material characterization and cross section analysis

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Presentation outline

<u>Introduction:</u>

- Objectives

<u>Developments:</u>

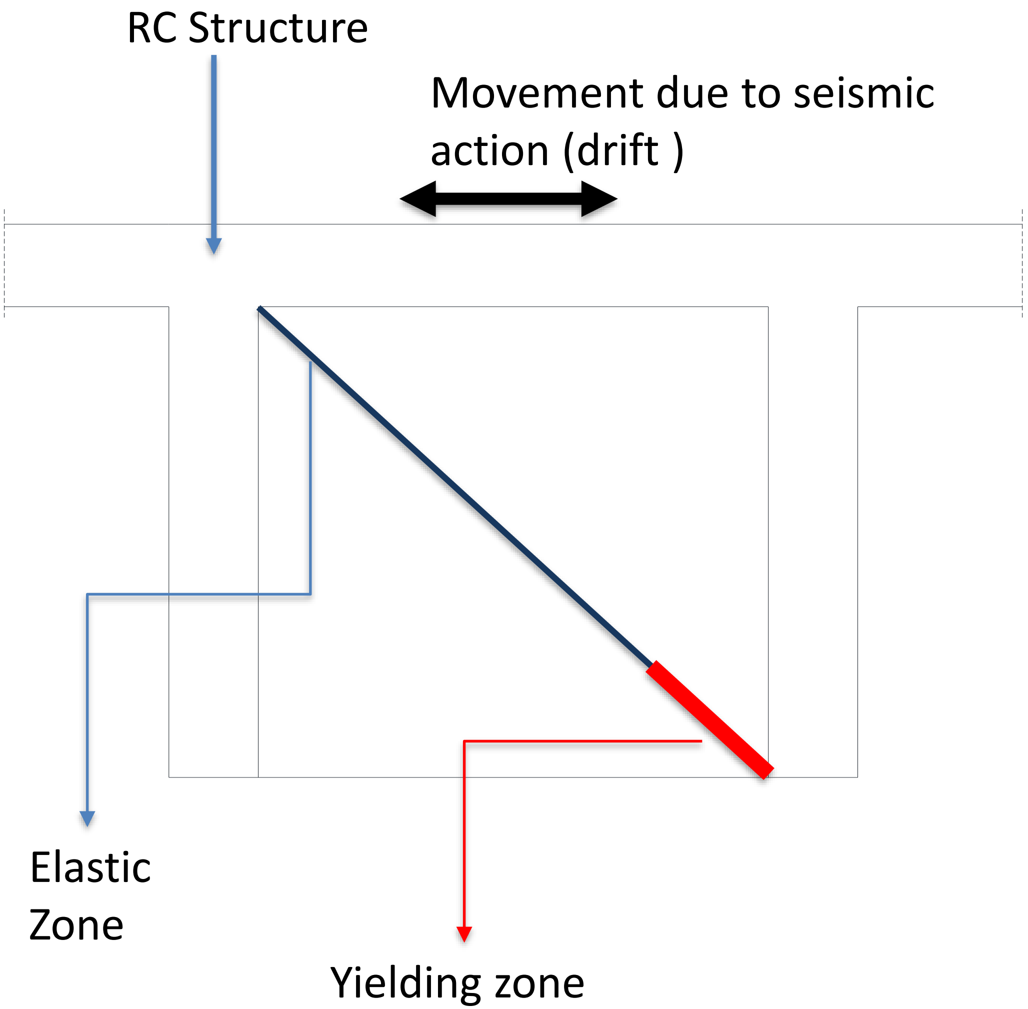
- Definition of the aluminium alloys targeted for the development of the BRD_AL prototype;
- Description of experimental results regarding the mechanical behaviour of aluminium alloys
- Parametrization of the mechanic behaviour of the selected aluminium alloy;

<u>Future work</u>

Development of BRD_AL Prototype

Objectives:

- Alternative to the dissipative bracing device paradigm: use an extruded aluminium alloy member without infill;
- 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;



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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

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Definition of the aluminium alloy

Heat treatment stage possibilities:

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

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

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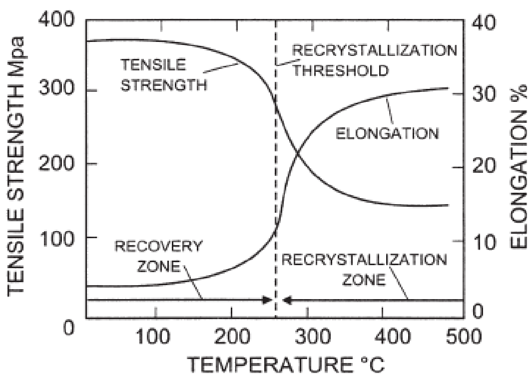
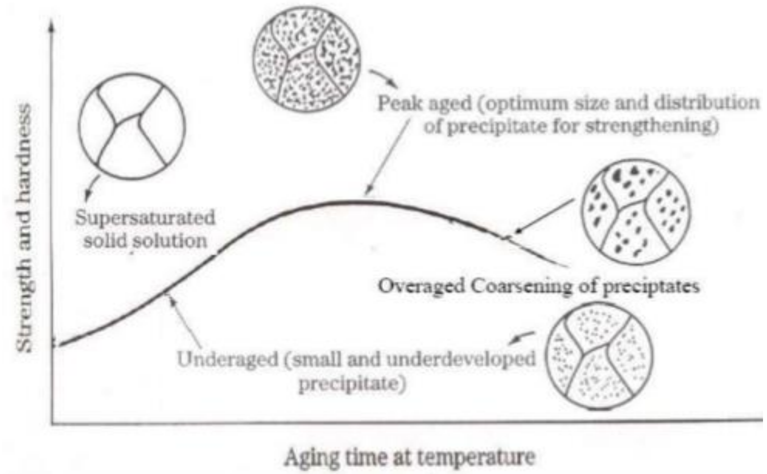
Aluminium Alloy - Thermal treatments – 6082 alloy

- 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

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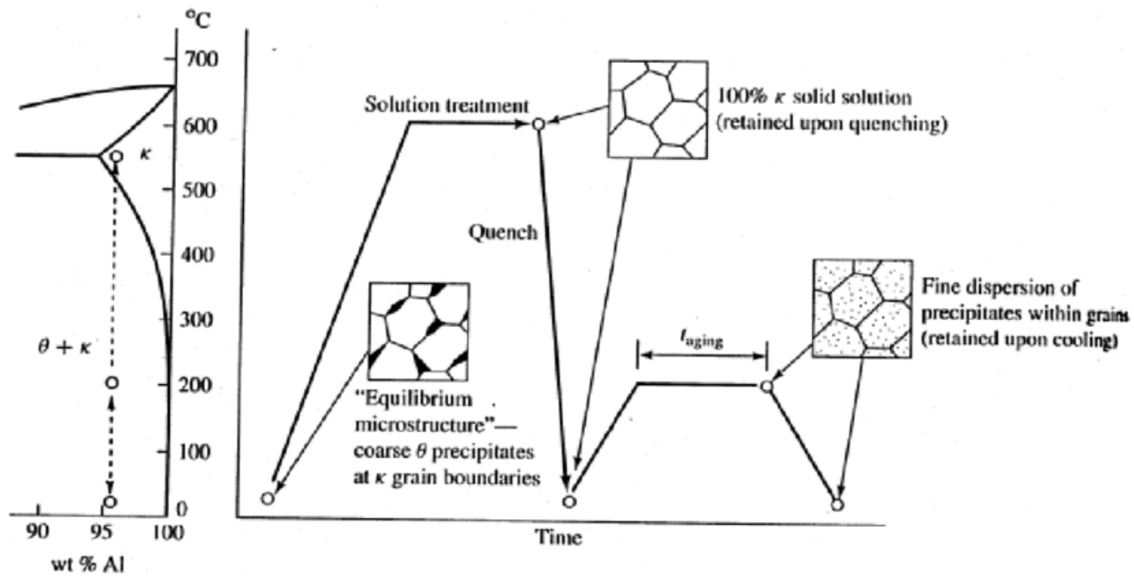
Aluminium Alloy - Thermal treatments

Thermal treatment stages:

- Solution treatment;
- Quenching;
- Artificial ageing



Precipitation transformations can be expressed by

$\alpha \rightarrow \alpha+\beta$

Metastable super saturated solution

More stable with he same crystal structure as α solid solution

Stable or metastable precipitate

<u>Proposed thermal treatments for the 6082 alloy:</u>

1. Solution treatment at 535ºC (45 min)+ageing at 190 ºC (2h);
2. Solution treatment at 535ºC (45 min)+ageing at 100 ºC (32h);
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

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Aluminium Alloy - Thermal treatments

Temper	Test specimen	Solution treatment		Ageing	
		Temp.(°C)	Time(min)	Temp.(°C)	Time(min)
AG190/120	6082-AG190/120	535	45	190	120
AG100/1920	6082-AG100/1920	535	45	100	1920
T6(**)	6082-T6	535(*)	60	160(*)	480

Temper	Test specimen	Annealing	
		Temp.(°C)	Time(min)
AN350/120	6082-AN350/120	350	120
AN280/480	6082-AN280/480	280	480

(*)(according to the supplier)

(**)(as supplied)

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Characterization of the mechanical behaviour of the selected alloys

Uniaxial tension tests

Uniaxial cyclic tests

Plate specimens

Rod type specimens (AW 6082 specimens);
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

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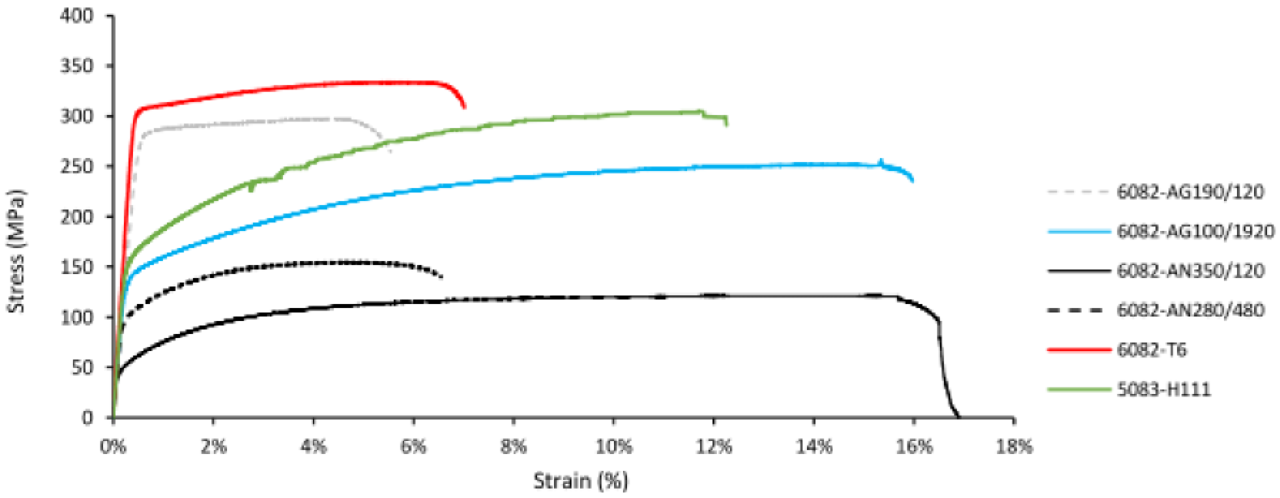
Uniaxial tension test results:



- The 6082-T6 specimen showed the highest performance in terms of yield and ultimate tensile strength. This case has been reported has peak hardness behaviour ;
- Between the 6082-T6 and 6082-AG190/120 specimens, the main difference lies in higher ultimate strength and strain, explained by precipitate coarsening due to slight overaging of the 6082-AG190/120 ;
- The 6082-AG100/1920 specimen exhibited lower yielding strength and higher plastic strain than the AG190/120 and T6. This behaviour might be explained by the under aged condition observed in other studies considering 100ºC ageing treatments;

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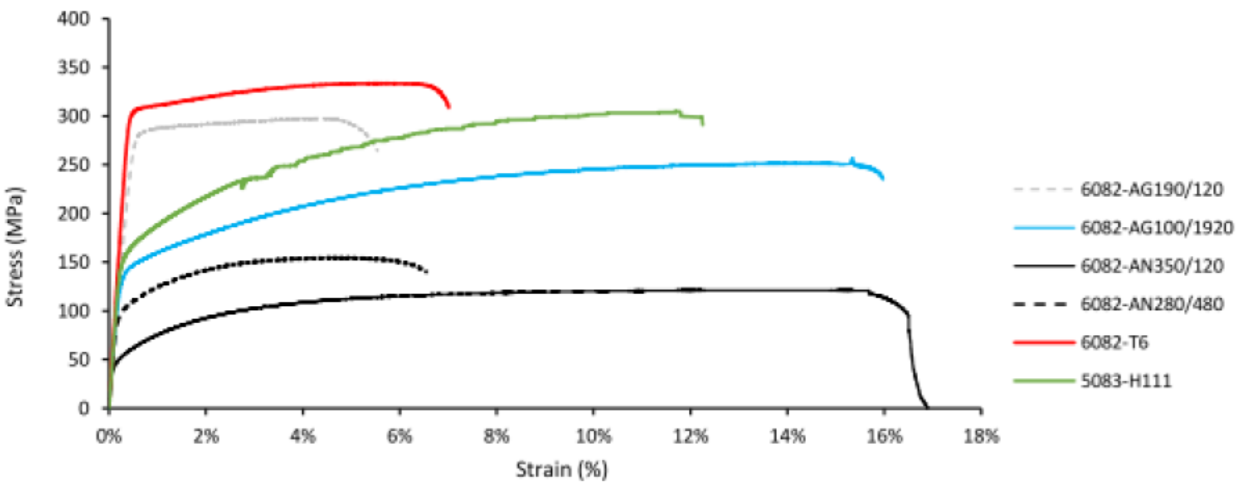
Uniaxial tension test results:



- The AN350/120 temper did not include a solubilisation process. Tempers with longer exposure to temperatures above 300 ºC enter the domain of severe overaged states. Significant decrease in strength, strain hardening increase and significant increase in ductility relatively to the AG190/120 and T6 tempers.
- The AN280/480 temper, also did not included a solubilization process. Annealing was different both in terms of temperature and time of exposure from the AN350/120. Significant decrease in both yield and ultimate tensile strength. A clear strain hardening rate increase was observed. Ductility was similar to the 6082-T6 and the AG190/120 test specimens.

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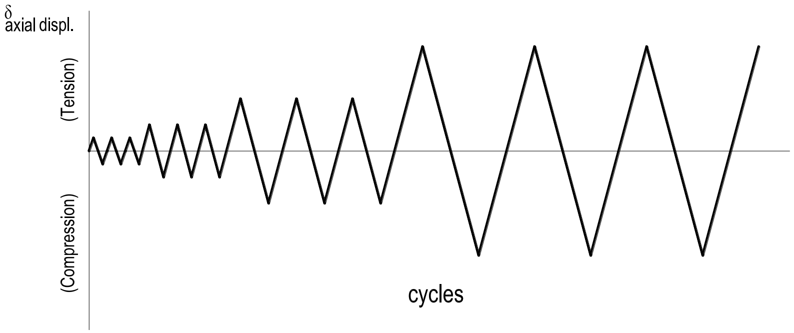
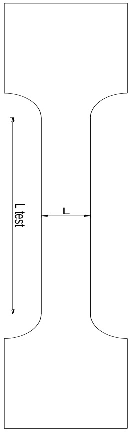
Uniaxial cyclic test results:

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



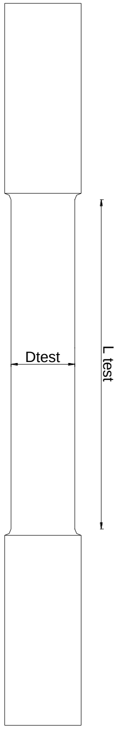
Loading history

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

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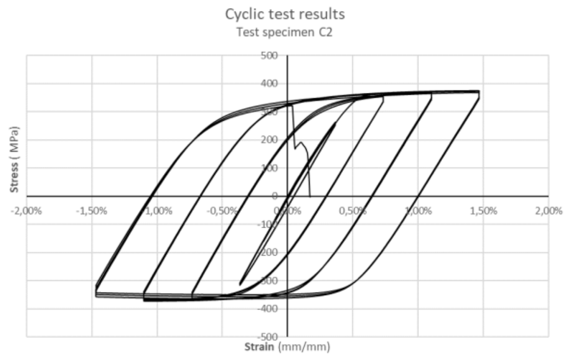
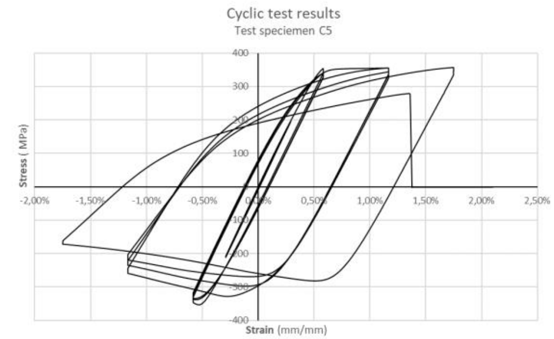
Cyclic behaviour – Test results

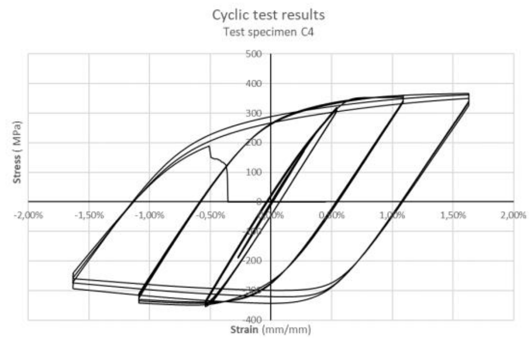
Test specimem C2 (λ_G=5) diagram show rather stable cycles until rupture, no visible effect of slenderness;

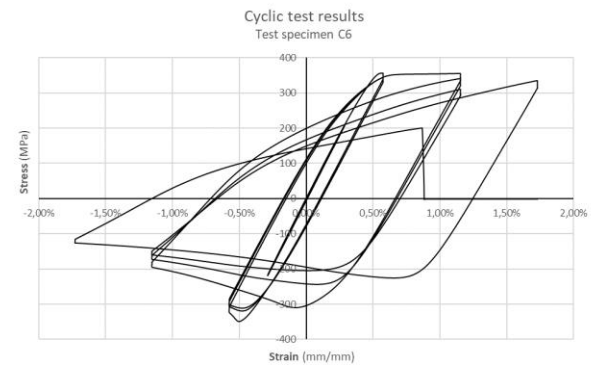
Test specimen C4, λ_G=7,19, the effect of slenderness is negligible in first cycles in plastic regime, although becomes evident in the final cycles before rupture. cycles remain rather stable until rupture. Loss of strength occurs mainly in the last cycles, more predominantly in the last half cycles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









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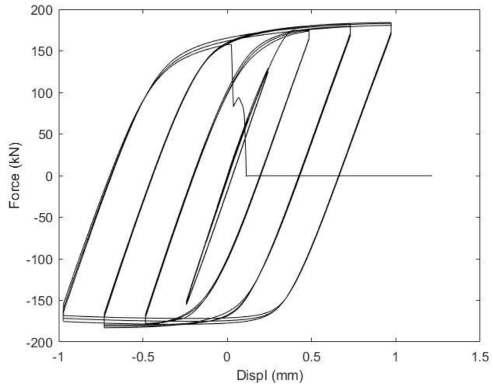
Cyclic behaviour – Test results

The 6082-AG100/1920 specimen showed significant symmetry with respect to tension and compression cycles. Noticeable isotropic and kinematic hardening. Low number of inelastic cycles;

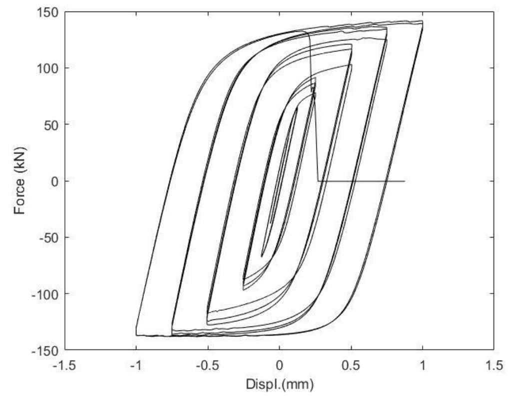
The 6082-AN350/120 specimen also showed symmetry with respect to tension and compression cycles. Noticeable isotropic and kinematic hardening. High number of inelastic cycles.

The difference in the alloys behaviour might be explained by the difference in precipitate density. Lower density of precipitates in an alloy implies that the distance between precipitates tends to be higher. The damage propagation of the material during cyclic loading tends to be slower, contributing to the delay rupture of the specimen.

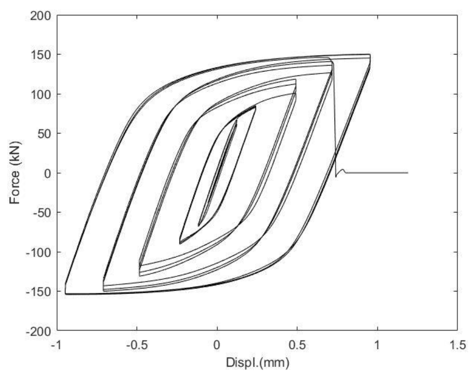
6082 T6



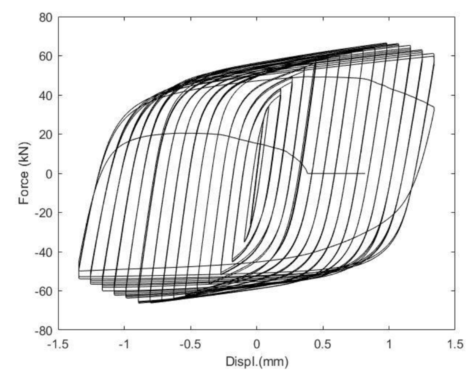
5083-H111



6082 AG100/32



6082 AN350/120



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Results assessments – Evaluation parameters – ATC 24 Recommendations

Loading capacity parameters

Test specimen	$\delta_y(mm)$	$Q_y(kN)$	$\delta_{max}(mm)$	$Q_{max}(kN)$	N_e
6082-T6	0,20	151,19	0,97	180,53	9
6082-AG100/1920	0,12	71,18	0,95	147,84	12
6082-AN350/120	0,04	27,00	1,24	66,50	90
5083-H111	0,13	68,40	1,00	140,17	11

Energy dissipation parameters

Test specimen	$E_{cum}(kNmm)$	E_{cum}^{norm}
6082-T6	2610	170
6082-AG100/1920	2342	567
6082-AN350/120	5366	9930
5083-H111	11720	2719

Deformation capacity parameters

Test specimen	μ_{max}	$\Delta\delta_{cum}(mm)$	$\Delta\delta_{cum}^{norm}$	$E \setminus \sigma_{y0.2}$
6082-T6	5	8,01	40	247
6082-AG100/1920	8	8,78	76	431
6082-AN350/120	31	61,70	1542	1249
5083-H111	8	7,97	63	397

- μ_{max} – Ductility ratio
- N_e – Number of inelastic cycles
- E_{cum} – Cumulative hysteretic area
- E_{curm}^{norm} – Normalized hysteretic area (normalized to 0.5xQ_yxδ_y
- $E/\sigma_{y0.2}$ – Ratio between tensile Young modulus and the reference yield stress

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Discussion:

- Assessment of the relevant features that were intrinsically related to material cyclic and inelastic performance

- Preferential parameters were considered to assess cyclic capacity. The recommendations indicated in the ATC24 guidelines are observed. Preference was given to deformation and energy dissipation capacities rather than to loading capacity. The 6082-AN350/120 alloy showed the highest values of normalized damage and energy dissipation, respectively, and the 5083-H111 alloy showed the highest value with regard total dissipated energy in testing.

- However, 6082-AN350/120 alloy showed highest values for number of inelastic cycles and normalized cumulative dissipated energy. Preference was given to the performance parameters N_e and E_{cum}^{norm}. Accordingly, the 6082-AN350/120 alloy showed best cyclic performance.

- Conclusions obtained by other authors were also taken into account for the definition of most suited alloy. DeMatteis et al., stated that the ratio $E/\sigma_{y\ 0.2}$ is particularly important parameter to be considered for material definition of any hysteretic dissipative devices. This parameter allows the developer to determine the more adequate material to ensure, not only that effective inelastic deformation occurs in the device before its occurs in the primary structure but also that inelastic deformation occurs prior to buckling of the hysteretic device.

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Numerical parametrization of the selected alloy

Selected material: AW 6082 - AN350/120

Experimental results of uniaxial tensile and cyclic tests

Calibration of behaviour models for material characterization

Numerical software ABAQUS:

- Numerical simulation of experimental tests through plate finite element analysis
- Simulation of the tensile deformation behaviour through the Deformation plasticity model, based of the Ramberg-Osgood model
- Simulation of the material cyclic behaviour through a combined isotropic-kinematic hardening model, based in the Chaboche-Lemaitre model

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Numerical parametrization of the selected alloy

Deformation plasticity : Ramberg-Osgood model

$$E\varepsilon = \sigma + \alpha\left(\frac{|\sigma|}{\sigma^0}\right)^{n-1}\sigma,$$

Combined isotropic-kinematic hardening model (Chaboche-Lemaitre) – Simulation of cyclic behaviour of the material

Isotropic hardening parameters

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

Kinematic hardening parameters

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

Formulation for the evolution of backstresses

$$\boldsymbol{\alpha} = \sum_{k=1}^{N}\boldsymbol{\alpha}_k,$$

Formulation for global backstress

$$\sigma_0 = \sigma\big|_0 + Q_\infty\left(1 - e^{-b\bar{\varepsilon}^{pl}}\right) + \sum_{k=1}^{N}\alpha_k$$

Formulation for the evolution of kinematic hardening of the material

C and γk are material parameters calibrated form the experimental results

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Numerical parametrization of the selected alloy

Tensile deformation: Ramberg-Osgood model

E GPa	σ_0 M Pa	n	α
68	33	3,93	0,3

Combined isotropic-kinematic hardening model (Chaboche-Lemaitre) – Simulation of cyclic behaviour of the material

Isotropic hardening parameters

Q_∞ MPa	k
26,7	5

Kinematic hardening parameters

C_1 MPa	γ_1	C_2 MPa	γ_2	C_3 MPa	γ_3	C_4 MPa	γ_4
90000	4500	9800	333	30	30	30	0,001

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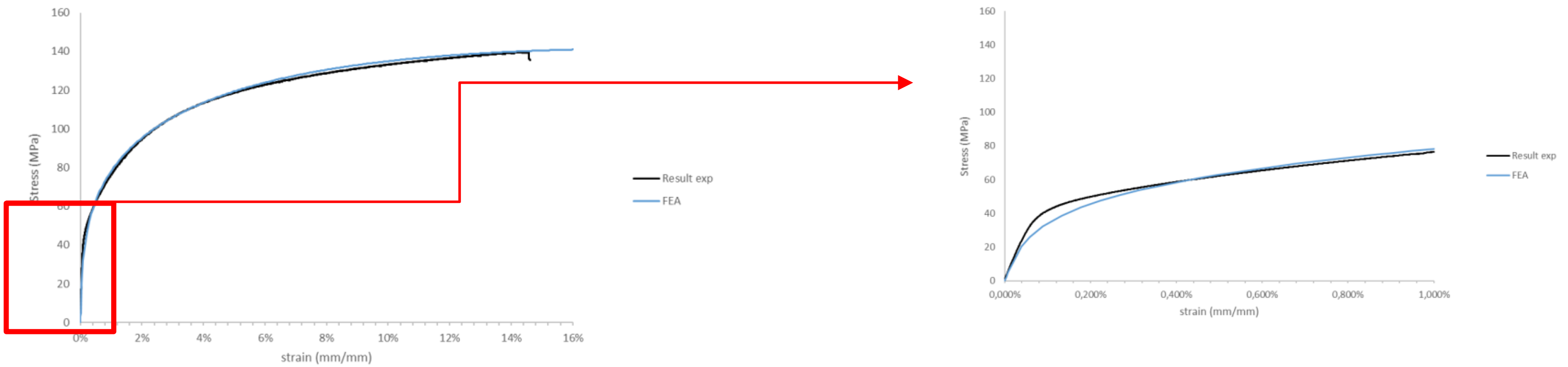
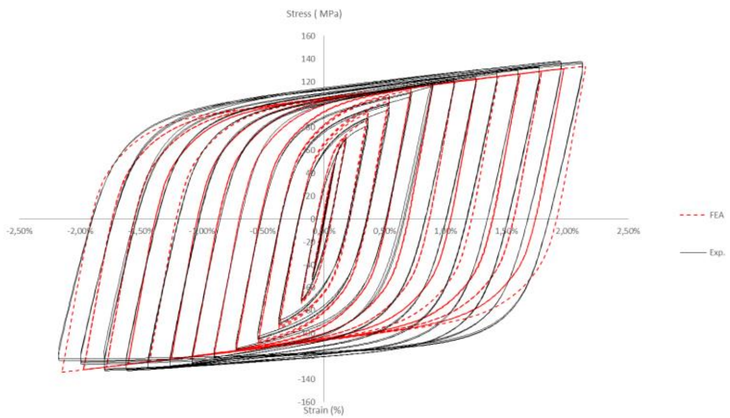
Numerical parametrization of the selected alloy

Deformation plasticity : Ramberg-Osgood model



Combined isotropic-kinematic hardening model (Chaboche-Lemaitre) – Simulation of cyclic behaviour of the material



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Principles regarding the numerical analysis of the dissipative device

Numerical assessment of the dissipative device

- Analysis and review of benchmarks of numerical analysis aluminium profiles, namely for mesh adequacy, finite element type and boundary conditions. The work of Odd Hopperstad in the analysis of cruciform aluminium profiles is considered has benchmark
- Assessment of imperfection sensitivity of different configurations of the device. Numerical studies of Hopperstad in this field are also applied in this study.
- Assessment of the cyclic behaviour of axially loaded aluminium profiles with different configurations, considering the cross-section limitations by extrusion

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Basic configuration of the dissipative device

Reference – work of Hopperstad et al. on aluminium cruciform profiles

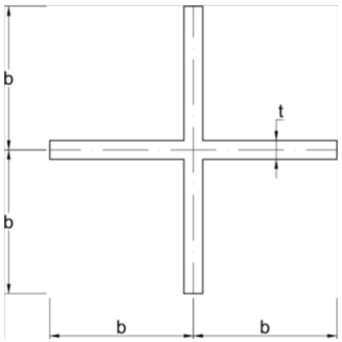
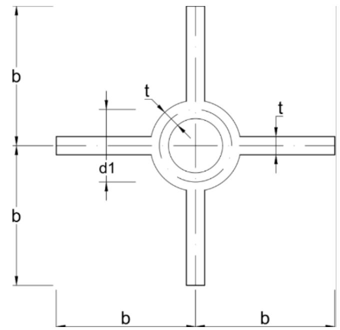
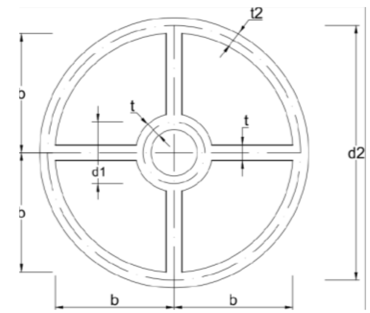
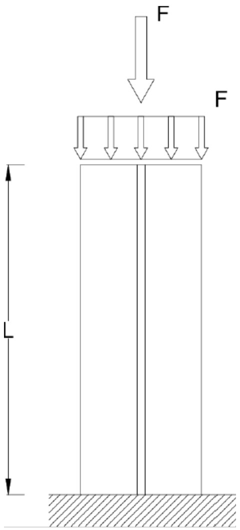


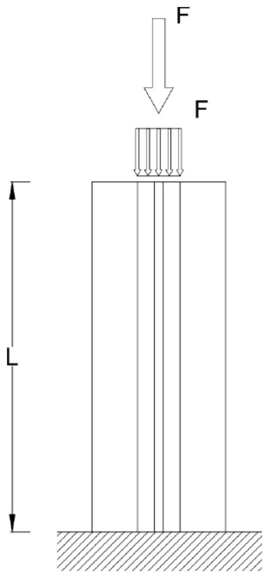
Plate instability

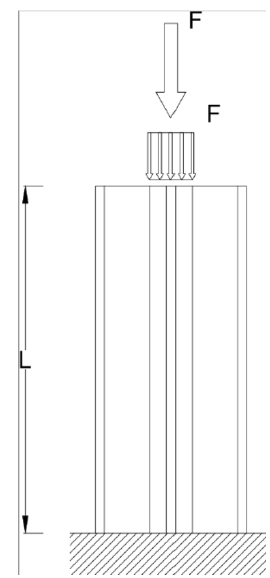






Combined effect of plate and cylinder instability





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Numerical analysis of the dissipative device

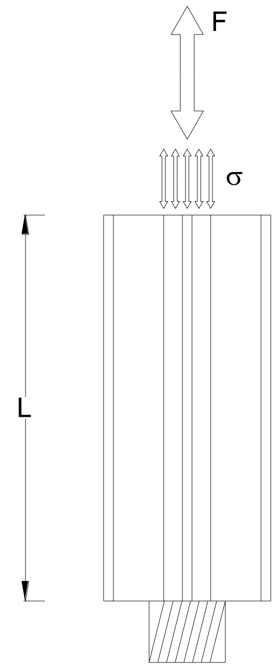
Assessment of the cyclic behaviour of the configured aluminium profile

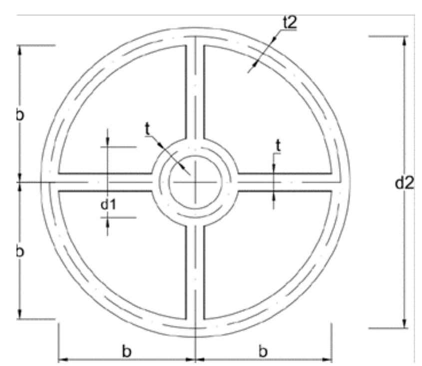
Hypothesis:

- Cyclic behaviour – Use combined isotropic-kinematic hardening behaviour model;
- Use S4R shell finite elements with max 4mm width;
- Loading – loading history with increasing displacement amplitude – Multiples of the yield displacement of the each profile configuration

Issues:

- Plastic buckling behaviour;
- Global buckling of the element Plates + Cylinders (Plate slenderness vs Cylinders slenderness);
- Effect of fatigue in the cyclic behaviour of the element
- Damage evolution





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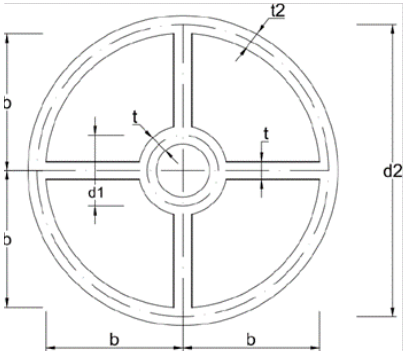
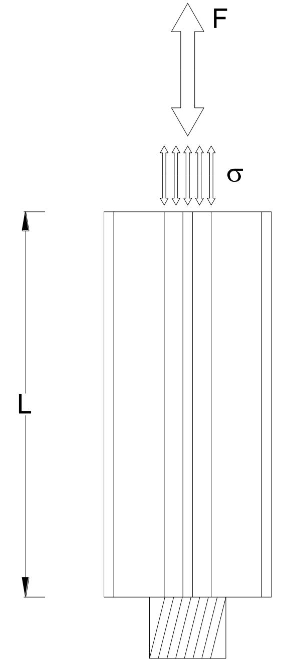
Numerical analysis of the dissipative device

Parametric analysis – Geometric variables



d1	d2	t	t2	Imperfection	L
mm	mm	mm	mm	mm	mm
236	36	2,5; 4,7; 6,8; 9	2,5; 4,7; 6,8; 9	0,1; 0,25; 0,5; 0,75	400; 700; 1000; 1300



- Imperfection defined as a % of plate length (plate connecting inner and outer cylinders)
- Different configurations of the aluminium profiles based on different combinations of the geometric variables
- Buckling analysis of each of the different configurations (1024)
- Maximum compression capacity of each of the different configurations – Definition of Nmax vs Slenderness curves - Comparison with EC9 buckling curves.

Work in progress: numerical calculations of 1024 different profile configurations

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Thank you for your attention