

## Mechanical characterisation of orthodontic superelastic Ni-Ti wires

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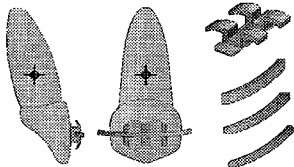
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**Abstract:** Nowadays, the orthodontic treatment is improving thanks to the introduction of Ni-Ti super-elastic alloy wires in the ordinary therapy. Indeed, laboratory tests performed in the last decade have shown that Ni-Ti super-elastic wires are able to satisfy the ideal requirements for fixed arch-wire appliance: high flexibility, minimal distortion or plastic deformation, light constant force production over a wide range of displacements. On the other hand, many orthodontic companies produce Ni-Ti arch-wires, without giving detailed specifications on their super-elastic characteristics. To improve the knowledge on real properties for these products, an experimental campaign on different commercial arch-wires has been started at the Laboratory of Biological Structure Mechanics (LABS) at the Politecnico di Milano (Italy). This work presents the first step of the research, concerning the comparison between the behaviour of four types of wires (two produced by ORMCO and two produced by 3M/Unitek) under monotonic and cyclic isothermal tensile tests. The results show significant differences between the products in terms of elastic modulus, stress values of the loading-unloading plateau, hysteresis amplitude, spring-back capacity, shape recovery capability, strain rate effect and fatigue behaviour.

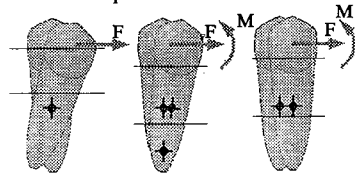
### 1 INTRODUCTION

The ordinary orthodontic therapy consists in applying forces and/or couples to the tooth crown by means of deformation of metallic wires, shaped as arch-wires (Fig.1): a stress state is generated into the periodontal ligament and, hence, in the alveolar bone, determining the tooth movement up to the reaching of the proper position [1]. The ideal arch-wire for fixed appliance treatment should be highly flexible, it should demonstrate minimal distortion or plastic deformation, it should exert light constant forces over a wide range of displacements [2], so to achieve mal-aligned tooth movement with the least possible tissue damage and patient discomfort [3].

Circular, rectangular or square section wires, shaped as arches, are fixed on the dental arch producing forces and couples as functions of their deformation.



Forces (F) and moments (M) generate the tooth movement following the appliance deformation which generally changes as a consequence of the tooth movement



**Figure 1:** Orthodontic appliance components (left side). Tooth movement depending on the force system applied to the tooth crown (right side).

Nowadays, this orthodontic treatment is improving thanks to the introduction of “new materials”. Indeed, laboratory tests, performed in the last decade on Ni-Ti super-elastic alloy wires [4][5], have shown that they are able to satisfy the requirements pointed out, even if the high sensitivity of the mechanical characteristics to thermo-mechanical treatments requires a lot of attention in the choice of the material for the therapy [6] [7]. On the other hand, many orthodontic companies produce Ni-Ti arch-wires, without giving detailed specifications on their super-elastic characteristics. To improve the knowledge on real properties for these products, an experimental campaign on different commercial arch-wires is in progress at the Laboratory of Biological Structure Mechanics (LABS) at the Politecnico di Milano (Italy).

## 2 MATERIALS AND METHOD

This work concerns the comparison between four types of super-elastic Ni-Ti arch-wires (Fig.2): two wires, produced by 3M/Unitek (Monrovia, CA), and, respectively, with a circular cross-section (diameter of 0.41 mm) and with a rectangular cross-section (dimensions 0.48 mm x 0.64 mm) and two wires, with the same cross-section geometries, produced by ORMCO (Glendora, CA). The wires are subjected to different isothermal tensile tests under displacement control. A pre-stress of 40 MPa is used as lower limit. Tests are realised using a MTS 858 TableTop machine (Fig.3).

For each type of wire the following tests are performed: 1) Monotonic tensile tests up to failure at different strain rates. 2) Cyclic loading and unloading tests. 3) Fatigue test.

In this first part of the planned experimental campaign, each test is performed five times: the mean value of the five measurements is reported. Other measurements are in progress, to have more significant results in the future.

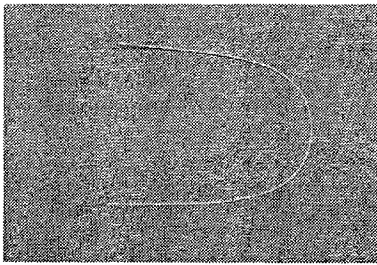


Figure 2: Ni-Ti super-elastic arch-wire

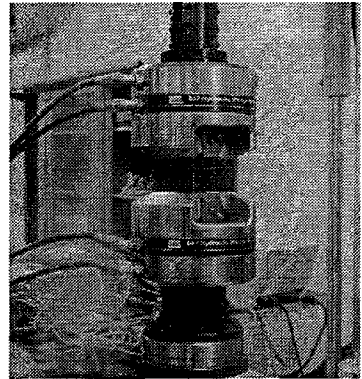


Figure 3: Test environment

The results are described in terms of stress-strain ( $\sigma$ - $\epsilon$ ) curve, where:  $\sigma = F / A_0$  is the nominal stress, i.e. the ratio between the force ( $F$ ) measured by the machine and the initial wire section area ( $A_0$ );  $\epsilon = \Delta L / L_0$  is the ratio between the displacement ( $\Delta L$ ) measured by the machine and the initial wire length ( $L_0$ ).

Table 1 shows the parameters considered as significant in describing the material behaviour curve, identified in the stress-strain ( $\sigma$ - $\epsilon$ ) curve (Fig. 4).

## 3 RESULTS

### 3.1 Monotonic tests up to failure at different strain rates

Monotonic tensile tests are performed to investigate the wire mechanical characteristics and their dependence from the strain rate. Indeed, the tests are performed at 4 different strain rates:  $\dot{\epsilon} = 0.000002 \text{ sec}^{-1}$ ;  $0.0002 \text{ sec}^{-1}$ ;  $0.006 \text{ sec}^{-1}$ ;  $0.02 \text{ sec}^{-1}$ .

The results (Table 2) show that viscous effects affect:

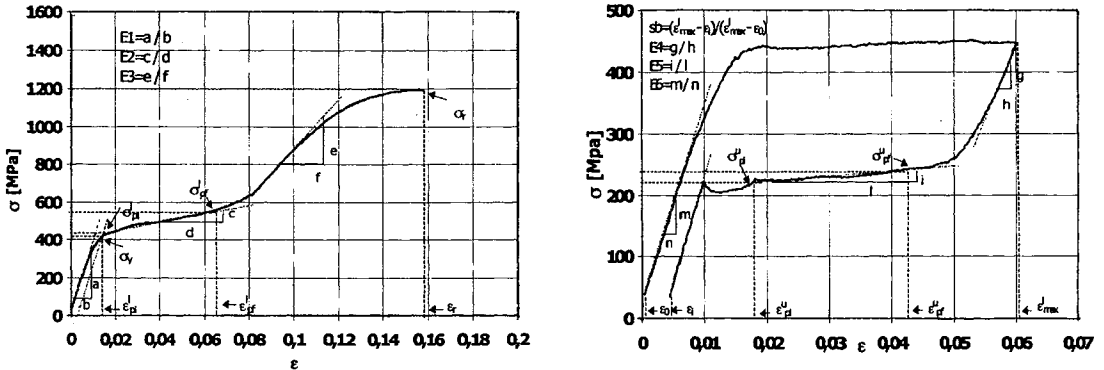
- The slope E2: increasing the rate, it grows for both types of wire.
- The plateau stress values: increasing the rate, they vary almost from 400 MPa to 600 MPa in ORMCO wires, almost from 450 MPa to 530 MPa in 3M/Unitek wires.
- The plateau strain amplitude: increasing the rate, it varies from 5% to 2% in the ORMCO circular wires, it remains constant around 5% in the ORMCO rectangular ones, around 3% in the 3M/Unitek circular wires, around 2% in the 3M/Unitek rectangular ones.

For both types of wire the following parameters are not dependent on the strain rate:

- The slope E1.
- The slope E3.
- The stress value at failure  $\sigma_r$ .
- The strain value at failure  $\epsilon_r$ .

**Table 1:** Significant parameters for characterising the material.

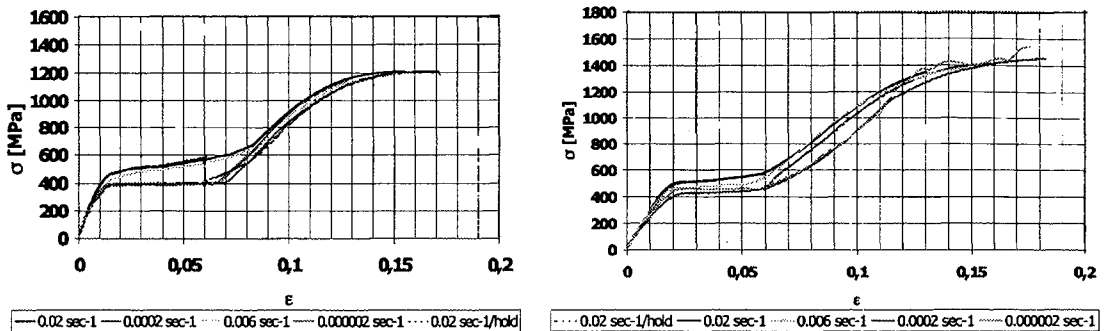
E1	Slope of initial part of stress-strain loading curve, i.e. elastic modulus of austenite.
E2	Slope of plateau region: during loading, the transformation from austenite to martensite takes place.
E3	Slope of final part of stress-strain loading curve, i.e. elastic modulus of martensite.
E4	Slope of initial part of stress-strain unloading curve, i.e. elastic modulus of martensite during elastic recovery.
E5	Slope of plateau region: during unloading, the transformation from martensite to austenite takes place.
E6	Slope of final part of stress-strain unloading curve, i.e. elastic modulus of austenite during elastic recovery.
$\sigma_y$	Yield stress, i.e. value of stress at which transformation occurs (it is calculated as the intersection between the material $\sigma$ - $\epsilon$ curve and the line having a slope equal to E1 and intersecting the strain axis at 0.2%).
$\sigma_{pi}^l, \sigma_{pf}^l$	Initial (i) and final (f) stress ( $\sigma$ ) values of the transformation plateau (p) during loading (l).
$\epsilon_{pi}^l, \epsilon_{pf}^l$	Initial (i) and final (f) strain ( $\epsilon$ ) values of the transformation plateau (p) during loading (l).
$\sigma_{pi}^u, \sigma_{pf}^u$	Initial (i) and final (f) stress ( $\sigma$ ) values of the transformation plateau (p) during unloading (u).
$\epsilon_{pi}^u, \epsilon_{pf}^u$	Initial (i) and final (f) strain ( $\epsilon$ ) values of the transformation plateau (p) during unloading (u).
$\sigma_r$	Stress value at failure.
$\epsilon_r$	Strain value at failure.
$\epsilon_i$	Residual strain, i.e. inelastic deformation.
Sb	Spring-back, i.e. ratio between the maximum strain reached in loading ( $\epsilon_{max}^l$ ) and the residual strain ( $\epsilon_r$ ) difference, and the maximum strain reached in loading ( $\epsilon_{max}^l$ ) and the initial strain ( $\epsilon_0$ ) difference.



**figure 4:** Significant parameters to describe material response, for a monotonic test up to failure (left side) and a cyclic test (right side).

**Table 2:** Comparison between the mechanical properties of ORMCO and 3M/Unitek wires during tensile tests up to failure at different strain rates.

STRAIN RATE	WIRE TYPE	Wire Section	E1 [MPa]	E2 [MPa]	E3 [MPa]	$\sigma_y$ [MPa]	$\sigma_{pi}^l$ [MPa]	$\sigma_{pf}^l$ [MPa]	$\epsilon_{pi}^l$ [%]	$\epsilon_{pf}^l$ [%]	$\sigma_r$ [MPa]	$\epsilon_r$ [%]
$0.2 \cdot 10^{-5} \text{ sec}^{-1}$	ORMCO	Circ.	46700	0	8500	400	420	420	2.0	7.0	1380	19
		Rect.	33330	0	11050	364	400	400	1.6	7.6	1200	18
	3M/Unitek	Circ.	25900	0	12730	440	460	460	2.0	5.6	1450	16
		Rect.	30000	1390	13330	360	420	450	2.0	4.0	1460	19
$0.2 \cdot 10^{-3} \text{ sec}^{-1}$	ORMCO	Circ.	47500	0	17010	392	440	440	1.6	6.1	1355	15
		Rect.	34170	0	14670	356	400	400	1.7	6.6	1210	16
	3M/Unitek	Circ.	22730	0	12730	419	420	420	2.1	5.7	1370	18
		Rect.	29200	0	15770	363	440	440	2.5	4.1	1460	17
0.006 $\text{sec}^{-1}$	ORMCO	Circ.	45000	2150	17500	480	490	580	1.6	5.6	1300	12
		Rect.	41770	2250	13200	403	456	543	1.8	6.2	1213	15
	3M/Unitek	Circ.	23660	1180	13620	445	456	490	2.4	5.6	1376	16
		Rect.	24150	2250	15300	435	475	525	2.7	4.7	1450	17
0.02 $\text{sec}^{-1}$	ORMCO	Circ.	50000	2000	15000	400	520	580	2.0	4.0	1310	15
		Rect.	43850	3430	13300	398	473	633	2.0	7.2	1203	15
	3M/Unitek	Circ.	27320	1770	13680	469	480	534	2.0	5.6	1364	14
		Rect.	29600	2200	15150	400	475	530	2.6	4.6	1440	17



**Figure 5:** Comparison between ORMCO rectangular wire tensile test responses at different strain rate (left side). Comparison between 3M/Unitek circular wire tensile test responses at different strain rate (right side)

Comparing the stress-strain curves at different strain rates (Fig. 5) it is evident that there exists a rate value above which the viscosity affects the responses. A relaxation test is carried out, in order to identify this value. The test consists in loading the wire at high strain rate ( $\dot{\epsilon} = 0.02 \text{ sec}^{-1}$ ) up to the 6% strain, holding constant the strain for 300 sec and then loading it again up to failure. It is found out that 300 seconds are sufficient to reduce the load (from 600 MPa to 400 MPa in ORMCO wires, and from 600 MPa to 450 MPa in 3M/Unitek wires), thus moving away from the stress-strain curve typical of high strain rate ( $\dot{\epsilon} = 0.006\text{-}0.02 \text{ sec}^{-1}$ ) and reaching the low strain rate ( $\dot{\epsilon} = 0.0002\text{-}0.000002 \text{ sec}^{-1}$ ) material curve. These results suggest to use a strain rate of  $0.0002 \text{ sec}^{-1}$  without viscous effects.

Figure 6 compares the responses of the four wire types during tensile test at  $\dot{\epsilon} = 0.0002 \text{ sec}^{-1}$ : the results show that at this strain rate the transformation plateau is horizontal and the plateau stress values are similar between the different wires, while the plateau amplitudes are quite different.

### 3.2 Cyclic tests at $0.0002 \text{ sec}^{-1}$ strain rate

In order to investigate the influence of the strain history on the material behaviour, two cyclic tests are performed:

- 1) 10 consecutive cycles up to 8%, 6%, 4% and 2% strain.
- 2) 10 consecutive cycles up to 2%, 4%, 6%, 8%, 6%, 4% and 2% strain.

The comparison (Fig. 7) between the responses at 6% strain after 10 cycles at 2% and 4% and the ones after 10 cycles at 8%, points out the strong influence of the previous deformations on the behaviour of both the types of wire. Figure 8 shows ORMCO and 3M/Unitek rectangular arch-wire responses during cyclic test at 2%, 4%, 6%, 8%, 6%, 4% and 2% strain. Comparing the results, it is possible to observe that:

- The ORMCO plateau region is wider than the 3M one.
- The ORMCO plateau slope during loading and unloading remains zero and the plateau stress value is almost constant in all the tests.
- The 3M/Unitek plateau slope during loading and unloading constantly increases and the plateau stress value strongly decreases in all the tests.
- In the ORMCO wires, the elastic deformation of martensite during loading starts at 7% strain and the stress reached at 8% is 500 MPa.
- In the 3M/Unitek wires, the elastic deformation of martensite during loading starts at 5% strain and the stress reached at 8% is 820 MPa.
- The areas of the hysteretic cycles of the ORMCO wires are wider than the one of the 3M/Unitek wires.

These observations point out the better capacity of ORMCO products to satisfy the requirements of an ideal arch-wire for fixed appliance treatment (defined in Section 1).

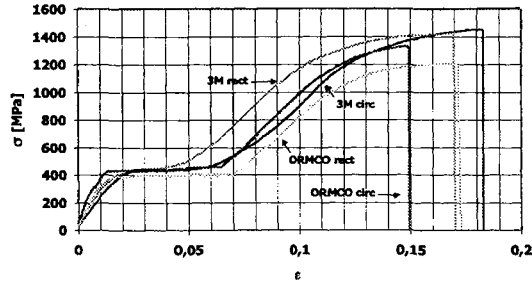


Figure 6: Comparison between ORMCO and 3M/Unitek different wire tensile test responses at 0.0002 sec<sup>-1</sup> strain rate.

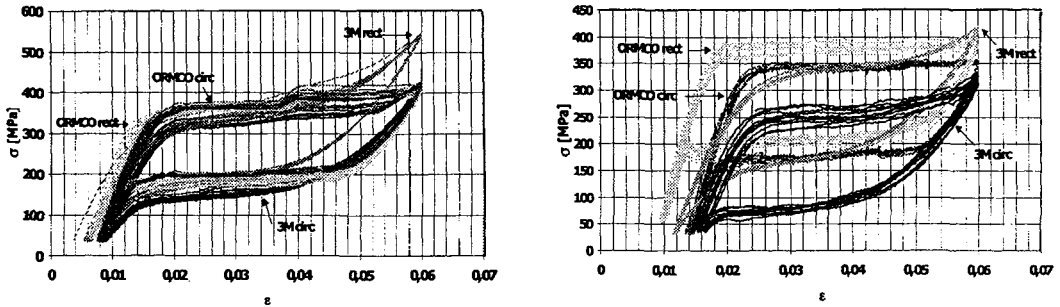


Figure 7: Comparison between ORMCO and 3M wire responses at 6% strain after cycles at 2% and 4% (left side). Comparison between ORMCO and 3M wire responses at 6% strain after cycles at 8% (right side).

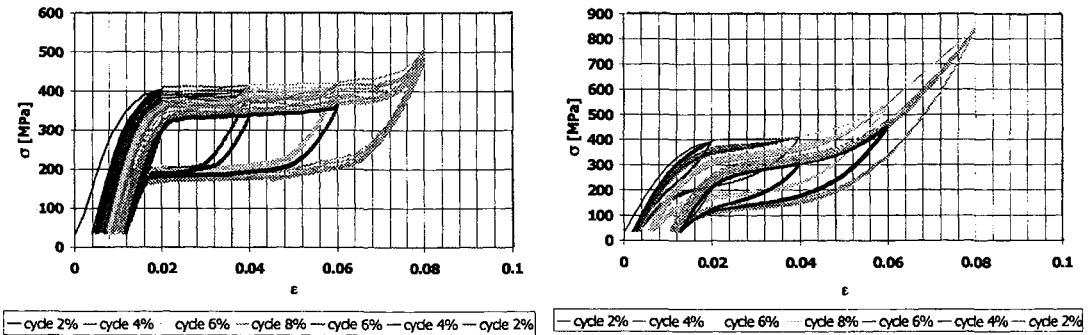


Figure 8: ORMCO rectangular arch-wire response during cyclic test at 2%, 4%, 6%, 8%, 6%, 4% and 2% strain (left side). 3M rectangular arch-wire response during cyclic test at 2%, 4%, 6%, 8%, 6%, 4% and 2% strain (right side).

### 3.3 Fatigue test

The Ni-Ti wires are stressed up to 6% strain for 250 cycles. Comparing the characteristic parameters calculated at the first and the 50<sup>th</sup> cycle, it results that:

- The ORMCO wire response is stabilised after 50 cycle, the 3M/Unitek one after 100 cycle.
- From the first and the 50<sup>th</sup> cycle, the ORMCO plateau stress value decreases of 110 MPa during loading and 40 MPa during unloading for circular type, of 150 MPa during loading and 50 MPa during unloading for rectangular type.
- From the first and the 50<sup>th</sup> cycle, the 3M/Unitek plateau stress value decreases of 135 MPa during loading and 90 MPa during unloading for circular type, of 110 MPa during loading and it disappears during unloading for the rectangular type.

The cycling effect is storing up inelastic deformation and reducing the plateau extension (Fig. 9).

After fifty cycles in ORMCO wires: a) The inelastic strain is more than 1%. b) For the circular type, the loading plateau finishes around 5.4% and the unloading plateau has a reduction of 15%. c) For the rectangular type, the loading plateau finishes around 4.8% and the unloading plateau has a reduction of 25%. After fifty cycles in 3M/Unitek wires: a) The inelastic strain is less than 1%. b) For both the circular and the rectangular type the loading plateaux finish around 4% strain and the unloading plateaux are totally disappeared.

For all the wires at the 50<sup>th</sup> cycle, the spring-back is equal to 100%, it means that the material is able to recover all the deformation.

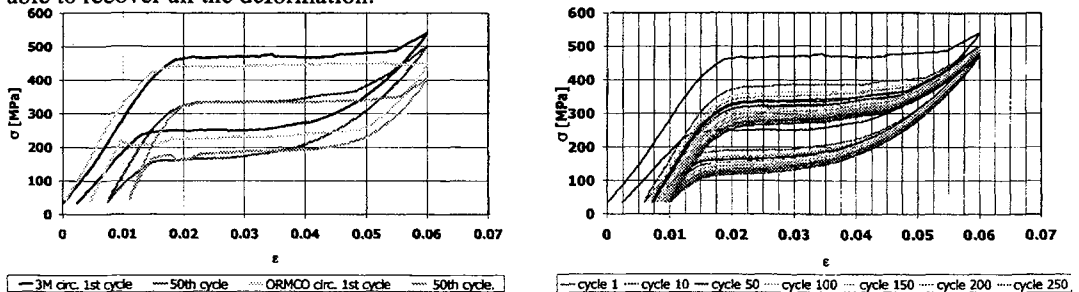


Figure 9: Comparison between ORMCO and 3M circular wire responses during the first and 50th cycle of the fatigue test at 6% strain (left side). 3M circular wire response during cyclic test at 6% strain (left side).

#### 4 DISCUSSION AND CONCLUSIONS

This work presents the first results of an experimental campaign devoted to investigate the mechanical properties of Ni-Ti super-elastic alloy arch-wires employed in the orthodontic therapy.

The tests point out some interesting differences, between theoretically similar devices, which can not be neglected during an orthodontic therapy. In particular, during tensile test up to failure, the Nitinol-Se produced by 3M/Unitek and the Ni-Ti produced by ORMCO show different elastic modulus, different slope in the transformation between austenite and martensite phase and in the martensite deformation. During cyclic tests, after an initial accumulation of inelastic strain (that goes between 0.25 to 0.9% in the first cycle), both ORMCO and 3M/Unitek wires show a good spring-back, a wide transformation plateau at constant stress (up to 6%), which remains stable in the case of ORMCO wire, while it is sensible to the strain history and to the number of test cycles in the case of 3M wires.

The next step foresees testing material in more realistic condition, that is under flexural and torsional loading.

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