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FLEXURAL BEHAVIOR OF A CONCRETE BEAM REINFORCED WITH METAL REBARS PRODUCED FROM A PSEUDO-ELASTIC NICKEL-TITANIUM ALLOY

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The use of concrete in the construction industry is widespread throughout the world, which increases the need for a better characterization of its technical aspects. In particular, there is a need for a better understanding of its poor performance when subjected to dynamic loads, which occurs due to its great stiffness and its little (if any) deformation capacity. Knowing that one of the ways to mitigate the poor behavior of concrete in case of dynamic loads is by improving the deformation capacity or ductility of the metallic reinforcement, the proposal to explore the behavior of a concrete beam reinforced with metallic rebars produced from a pseudo-elastic Nickel-Titanium alloy becomes highly desirable. This experimental research aims to verify the flexural behavior of a concrete beam reinforced with Nickel-Titanium rebars. In this regard, the requirements suggested by the technical standard in force were carefully followed, relying mainly on the international standard ASTM C78. Concrete specimens were produced either reinforced with conventional steel rebars; or reinforced with Nickel-Titanium rebars. The results showed that, although the Nickel-Titanium rebars specimens presented a modulus of rupture 26.48% lower, their displacement was about 642.79% greater in relation to specimens with conventional steel rebars, in addition to presenting a partial recovery of the beam's initial position even after complete concrete breakage.

Keywords: smart materials, flexural test, special structures

1 INTRODUCTION

Reinforced concrete is a widely used material all over the world. Some countries use it on a large scale due to its better cost-effectiveness compared to other materials [1]. The use of reinforced concrete provides a very secure structural system in static actions. Nevertheless, failures are usually abrupt. In addition to that, the steel used in the reinforcing rebars may undergo corrosion due to environmental factors, which may cause the system to fail, often prematurely [2].

Several studies have employed shape memory alloys in the structures of civil construction sites. Part of these studies, presented here, involved the use of different shape memory alloys as concrete reinforcement in order to soften the actions of earthquakes and, as well, in the prevention and damage control in structures.

Shresta et al. [3] compared the performance of shape memory alloy-reinforced bridge pillars and steel-reinforced pillars applying a seismic assessment methodology based on probabilistic performance, considering the combination of peak displacement and residual deformation. The results indicated benefits in the use of shape memory alloy reinforcement in the plastic region of the ends of pillars built on sites of moderate or high seismic action.

Ghafoori et al. [4] verified the behavior of an iron-based shape memory alloy, composition Fe-17Mn-5Si-10Cr-4Ni-1 (V, C), under high temperature conditions. The alloy was tested in two thicknesses, being 0.5 and 1.5 mm. It was considered that the activation of the shape memory effect occurs at a temperature of 114ºC for the beginning of the phase transformation and 116ºC for the end. The test was performed by varying the stress at 0; 80; and 240 MPa, and increasing the temperature in the scale of 50ºC/min. Trial times were 15, 30, 45 and 60 minutes. The authors realized that the behavior of the alloy showed proportional results as to the thicknesses used in the tests.

After the experimental checks, the authors used the ABAQUS software to perform simulation analyses of the alloy inserted as reinforcement in the concrete. The results showed better performance as to deformations at high temperatures, because, in terms of mechanical strength, the material followed the strength of the concrete; and the higher was the loading, the lower was the temperature failure coefficient [4].

When testing Fe-Shape Memory Alloy specimens, the failure temperature was greater than 500 ºC; when inserted into concrete, the failure was approximately 270ºC. Namely, by reaching these temperatures, the pre-stressing was impaired. Thus, the authors suggest applying thermal protection treatment to the concrete [4].

Roh and Reinhorn [5] analyzed the behavior of segmented pillars of a bridge, reinforced with shape memory alloy in the effect of superelasticity. Quasi-static cyclic tests were performed on four different types of arrangement: pillars with unbonded joint segments; pillars with unbonded joint segments and with a shape memory alloy yield device at the base; pillars with bonded joint segments; pillars with bonded joint segments and with a shape memory alloy yield device at the base.

The main objective of this paper was to analyze the hysteresis of the pseudoelastic/superelastic alloy in several cases: axial load strength; lateral load strength; and, in temperature variation. The authors found that the alloy ensures greater advantages to the system with respect to plastic deformation recovery, axis repositioning, dissipation energy stabilization, and high system ductility. Computational simulations have shown that the alloy has great potential of use for structural system safety in earthquake situations [5].

In the current research, the proposal to use Nickel-Titanium (NiTi) alloy to replace steel occurred for two main reasons: first, due to the ability to recover from larger deformations; and second, due to the high corrosion resistance [6,7]. This alloy is contained in the intelligent material classification, and can have Shape Memory effect (recovery from deformations after heating of the deformed material) or the Pseudoelastic/Superelastic effect (instantaneous self-recovery from deformations after load relief) [8,9]. Figure 1 shows the shape memory effect and Figure 2 the pseudoelastic/superelastic effect, which are determined by the phase (initial and transformation) of the material.

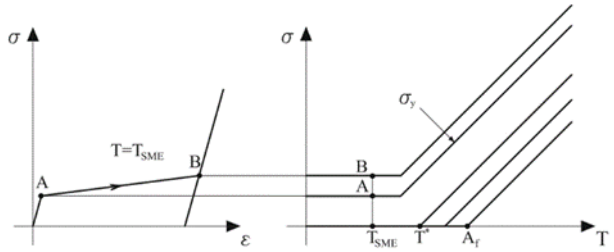

Fig. 1. Stress-Strain Shape Memory theoretical graph [10]

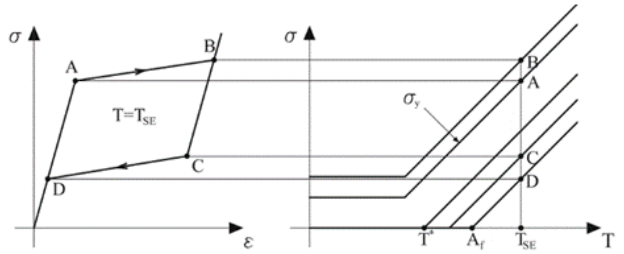

Fig. 2. Pseudo-elastic behavior theoretical graph [10]

Although Nickel-Titanium is a material with great potential to replace steel in reinforced concrete, especially in specific cases of new features and structural safety, it is an alloy that is still not widespread and its use is expanding in several applications [6]. Some basic tests are fundamental to understand the behavior and check compliance with the Standards for material use (national and international). From this perspective, this work relies on two main ones: ASTM C78 and Brazilian Technical Standards 12142.

The standard four-point flexural test was used on concrete beams reinforced with steel rebars and concrete beams reinforced with Nickel-Titanium rebars, where the verification of the mechanical properties of reinforced concrete was obtained by analyzing the intrinsic aspects of the materials and verified through experimental tests. The pseudoelastic/superelastic property of the Nickel-Titanium alloy tends to provide a very specific mechanical behavior to the reinforced concrete system, because, in addition to higher deformability, it is expected that there is partial recovery of a fractured structural element and enables structural functionality (even if limited) in order to mitigate structural collapse. Furthermore, this is basically what occurred in the tests, as the conventional concrete beam reinforced with steel rebars withstood moderately higher loading than the one reinforced with Nickel-Titanium, although, the deformation was relatively higher in the system containing the pseudoelastic/superelastic alloy.

2 EXPERIMENTAL STUDY

This research is based on international standards, as mentioned earlier, mainly ASTM C78. It is important to note that Brazilian Standard 12142 is, for the most part, based on the international standard mentioned, and, due to the research being conducted in Brazil, it always appears as support to substantiate the similarity between them. Hereinafter are the parameters and materials used for the experimental research.

2.1 Preparation of the specimens

The test specimens were manufactured according to the dimensions proposed by ASTM C78 (also fits the Brazilian Technical Standards 12142:2010) for four-point flexural tests, having dimensions of 150 x 150 x 500 mm. The reinforcements were inserted in the tensile region of the beams and were calculated according to Brazilian Technical Standards 6118:2014, which establishes that the minimum steel area (A_S, min) must be 0.208% of the cross-sectional area. Therefore, for each 150 x 150 x 500 mm beam, 37.71 mm² steel and 36.93 mm² Nickel-Titanium sections were used in the tensile regions, which represents 0.335 and 0.328%, respectively (Figure 3).

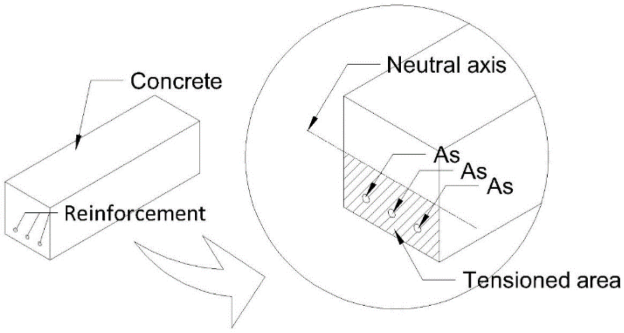

Fig. 3. Definition of the tensile area in the cross section

2.2 Materials

This research seeks an alternative system for situations that demand high performance. Therefore, structural micro-concrete with a characteristic compressive strength of approximately 50 MPa (high strength) was used. The steel used was CA-60 with a diameter of 4.2 mm. Table 1 presents the specifications of the metallic materials used as reinforcement for the concrete matrix; the shape memory alloy used has a pseudoelastic/superelastic effect.

Table 1. Properties of the Nickel-Titanium rebars used [11]

Physical and mechanical properties	
Melting Point (°C)	1310
Density (g/cm³)	6.5
Electrical Resistivity (µ ohm-cm)	82
Modulus of Elasticity (GPa)	(Austenite) 70 to 90
Coefficient of Thermal Expansion (°C)	11 x 10-6
Tensile Strength (MPa)	≥ 1070
Yield Strength (MPa)	≥ 390
Total Extension (%)	≥ 10
Chemical composition	
Nickel	55.8 pp% (approximately)
Titanium	44 pp% (approximately)
Carbon	≤ 0.05 pp.%
Oxygen	≤ 0.02 pp.%

2.3 Test setups

The four-point flexural tests were performed according to the criteria established by ASTM C78 and Brazilian Technical Standards 12142:2010, using specific equipment in a universal machine model EMIC 23-100 with a speed of 0.9 MPa/s. Following the specifications of these standards, Equation 1 was used for the tests that caused fracture in the middle third; and Equation 2, for the tests that caused fractures outside the middle third.

$$f_{(ct,f)} = F\,l/b\,d^2 \quad (1)$$

$$f_{(ct,f)} = 3Fa/bd^2 \quad (2)$$

Where:

$f_{(ct,f)}$: modulus of rupture (MPa);

F: maximum applied load indicated by the testing machine (N);

l: span length (mm);

b: average width of specimen at the fracture (mm);

d: average depth of specimen at the fracture (mm); and

a: average distance between line of fracture and the nearest support measured on the tension surface of the beam (mm).

In order to verify the internal loading (stress exerted on the reinforcement), devices with calibrated extensometers on the universal testing machine were used and inserted in the tensile region closest to the bars; Figure 4 shows the devices used. It is important to emphasize that the measurement of the devices was used to verify that the development of the tests would occur in a proportional way between the materials used; and, both had identical performance to the calibration curves, i.e., it was validated that the load was homogeneously distributed on the systems.

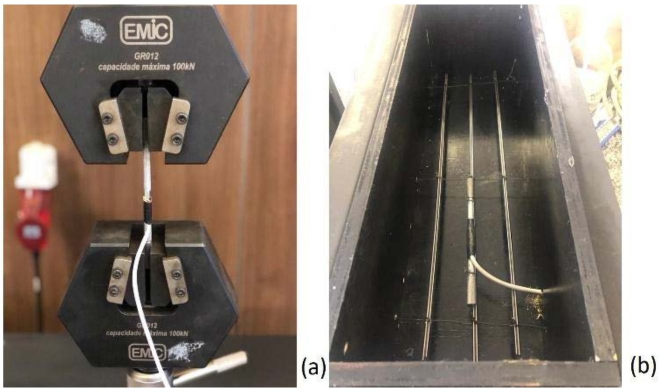

Fig. 4. Device with extensometer for checking the development of internal forces during the test. (a) calibration of the device on a universal testing machine; (b) inserting the device into the reinforcing rebars.

3 EXPERIMENTAL RESULTS

Three specimens of each Beam were manufactured and were executed according to the methodology and procedures described previously. The test specimens were given the nomenclature listed in Table 2.

Table 2. Specimen list with reinforcement material specifications, dimensions and nomenclatures

Name	Reinforcement Material	Dimensions (mm)
beam-1	Steel	150.97 x 151.42
beam-2	Steel	150.18 x 150.65
beam-3	Steel	150.91 x 151.36
beam-4	Nickel-Titanium	150.65 x 150.49
beam-5	Nickel-Titanium	148.49 x 151.50
beam-6	Nickel-Titanium	150.62 x 150.77

The micro-concrete strength after 28 days was 55.62 ± 5.52 MPa, verified by compression testing in the universal machine EMIC 23-100. Table 3 presents the results obtained for each cylindrical specimen (100 x 200 mm).

Table 3. Axial compression tests performed according to ASTM C39 and Brazilian Technical Standards 5739

Name	Dimensions [mm]	Compressive strength [MPa] (after 28 days)	Average compressive strength [MPa]
CP-1	100.93 x 201.68	49.43	55.62 ± 5.52
CP-2	100.35 x 199.86	57.39	
CP-3	100.12 x 200.53	60.04	

Therefore, according to the standards used in this research, the strength obtained allows the classification High Strength for the micro-concrete used.

3.1 Flexural behavior of beams

The specimens (identified in Table 4) of the concrete beams reinforced with conventional steel rebars showed the following results:

Table 4. Results of steel reinforced beams in flexural strength test

	beam-1	beam-2	beam-3	Average
Load [kN]	60.54	54.94	63.35	59.61 ± 3.50
Displacement [mm]	9.92	11.06	10.44	10.47 ± 0.47
Modulus of rupture [MPa]	6.61	7.25	8.25	7.37 ± 0.67

The evolution of the tests during loading of the concrete beams reinforced with steel rebars can be verified in Figure 5, which presents the Load x Displacement Graphs of the three tested beams.

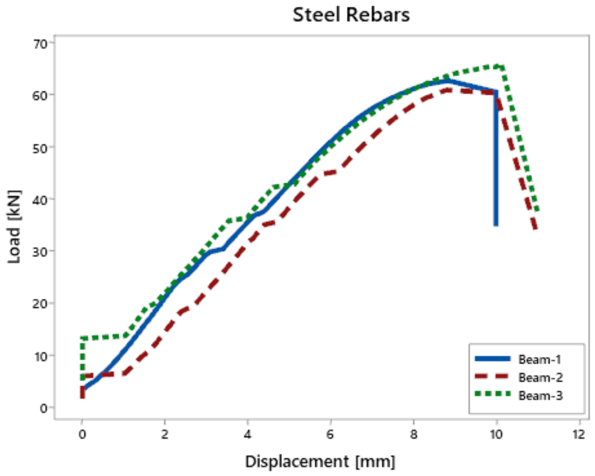

Fig. 5. Load-Displacement graph of the concrete beams reinforced with steel rebars.

The development of the tests was proportional, presenting very close values among them, and mechanical failure occurred in all three specimens, both in the reinforcement and in the matrix. Figure 6 shows the fracture occurred during the tests, where it is possible to see that only beam-1 had the fracture outside the middle third of the beam, and Equation 2 was used to calculate the modulus of rupture. Beam-2 and beam-3 had fractures in the middle third of the beam and therefore it was possible to use Equation 1 to calculate the modulus of rupture. It is important to note that when molding the specimen there may be some slight variations in the dimensions and that these are accepted. However, these variations can cause the fracture not to occur in the middle third of the beam, and for these cases, ASTM C78 carefully suggests using specific equations that specify only the maximum moments in the results, so the specimen is not discarded.

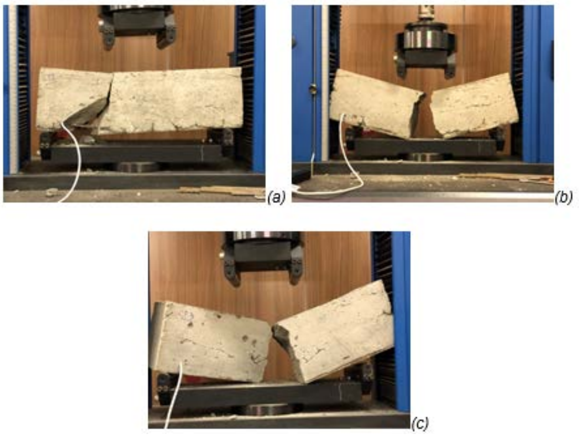

Fig. 6. Failure of the concrete beams reinforced with steel rebars in the flexural strength test. (a) beam-1; (b) beam-2; (c) beam-3.

The fractures occurred abruptly. Figure 7 shows details of the reinforcement after the test is complete. The steel rebars showed a weakly ductile failure characteristic, as expected.

Fig. 7. Detail of the steel rebar fractures after completion of the test.

The specimens (identified in Table 5) of the concrete beams reinforced with Nickel-Titanium rebars showed the following results:

Table 5. Results of the concrete beams reinforced with Nickel-Titanium rebars in flexural strength test.

	beam-4	beam-5	beam-6	Average
Load [kN]	43.89	42.82	36.54	41.08 ± 3.24
Displacement [mm]	66.12	66.41	69.36	67.30 ± 1.46

	beam-4	beam-5	beam-6	Average
Modulus of rupture [MPa]	5.79	5.65	4.80	5.42 ± 0.44

The evolution of the tests during loading of the concrete beams reinforced with Nickel-Titanium rebars can be seen in Figure 8, which presents the Load x Displacement Graphs of the three tested beams.

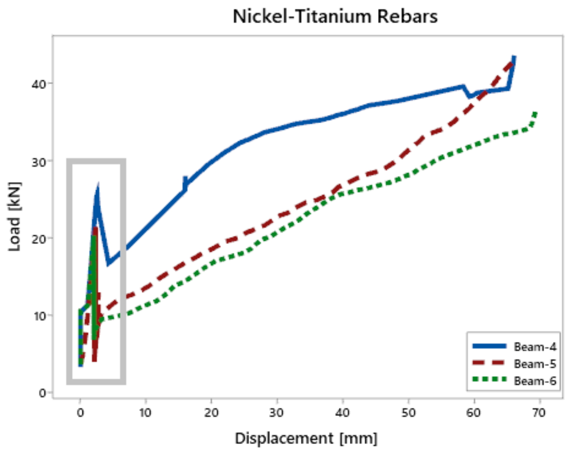

Fig. 8. Load-Displacement Graph of the concrete beams reinforced with Nickel-Titanium rebars

In this case, there was mechanical failure in the concrete, but not in the reinforcement. In the first stage, at approximately 23 ± 3.60 kN, the concrete broke abruptly (highlighted region in the graph), but the reinforcement continued to provide stability and mechanical strength, whereby the test was terminated due to the limitations of the displacement capacity of the testing machine. Figure 9 shows the fracture that occurred in the concrete during the tests, where it is possible to see that all beams had the failure in the middle third of the beam and, therefore, it is possible to use Equation 1 to calculate the modulus of rupture.

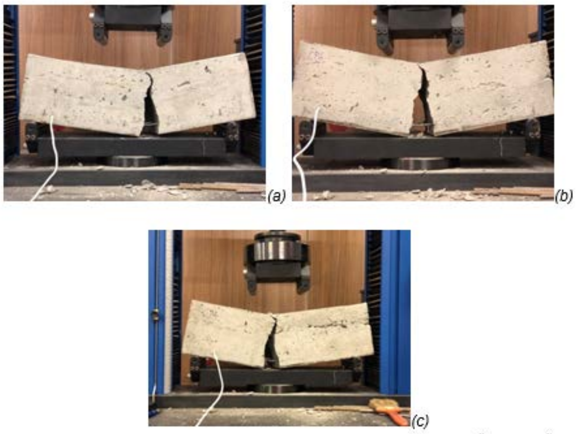

Fig. 9. Failure of the Nickel-Titanium reinforced beams in the flexural strength test. (a) beam-4; (b) beam-5; (c) beam-6.

Figure 10 shows in detail that the Nickel-Titanium rebars did not break and, over an unquantified distance, it slipped into the system. Although, the friction and adhesion stresses held a portion of the reinforcement in place, mechanically stabilizing the specimen.

Fig. 10. Detail of the Nickel-Titanium rebars after completion of the test.

To achieve the reinforcement cross-sectional area for the concrete beams reinforced with Nickel-Titanium rebars, two bars were used in each position (total of six bars per beam). The slippage that occurred demonstrates that the surface did not favor adhesion as expected, according to the pullout study made by Silva [11].

3.2 Discussions

From the experimental results presented above, it is possible to perceive that for the same section of Steel and Nickel-Titanium rebars, the materials had different mechanical behaviors. Whilst for the Steel rebars, the concrete beam withstood greater load and the steel rebars broke immediately after concrete failure, while the concrete beams reinforced with Nickel-Titanium rebars withstood less load, but with much greater displacement and there was mechanical support of the system even after concrete rupture. Figure 11 presents the Load vs. Displacement graph, considering the average values of the results of the tested beams. The concrete beams reinforced with steel rebars withstood a load of 59.61 ± 3.50 kN during the flexural strength test, achieving a modulus of rupture of 7.37 ± 0.67 MPa. The steel rebars broke in all cases and the specimen recorded a displacement of 10.47 ± 0.47 mm, representing conventional behavior. The steel specimen showed a higher modulus of rupture and little displacement (brittle).

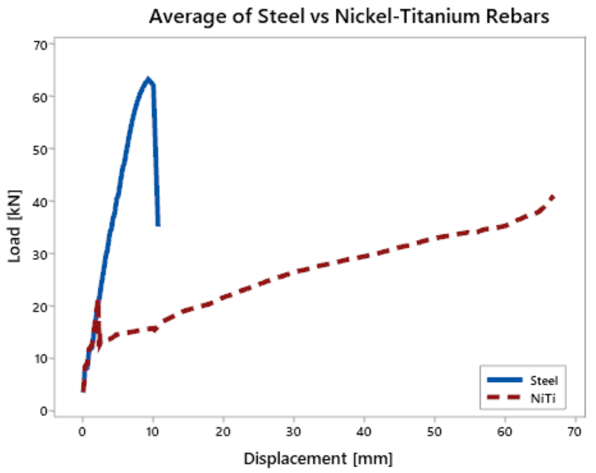

Fig. 11. Comparison of Load-Displacement curves of the averages of the reinforcements used.

The concrete beams reinforced with Nickel-Titanium rebars resisted less load (41.08 ± 3.24 kN), with a modulus of rupture of 5.42 ± 0.44 MPa. However, the behavior of the system was completely specific. During the test, the displacement (67.30 ± 1.46 mm) was only interrupted due to limitations of the displacement capacity of the universal machine. The specific equipment for four-point testing (ASTM C78 and/or Brazilian Technical Standard 12142:2010), in the available model, has a working space of 70 mm. Comparing the displacement values, the Nickel-Titanium reinforcement rebars provided greater safety to the system, as there was no abrupt collapse and failure of the beam.

Analyzing the graph presented in Figure 5.1, the first drop in the Nickel-Titanium curve represents the time at which the concrete broken in the middle third, splitting the beam in two parts. However, the machine continued to record the increase in supported load until it reached the machine stroke limit (limitations of the displacement capacity of the universal machine). This can be verified as standard in all tests of this material. It is important to emphasize that, although the results are positive, there has been some slippage of the Nickel-Titanium rebars. Hence, suggesting that better surface treatment should be done in order to optimize performance.

4 CONCLUSIONS

- the Nickel-Titanium reinforcement rebars provided greater displacement for the system. This demonstrates greater ductility of the reinforcement, providing greater stability in cases of dynamic loading, and also makes the fracture of the structural element less abrupt;
- in case of collapse, the Nickel-Titanium reinforced system is safer;
- the Nickel-Titanium rebars withstood the loading even with total concrete failure;
- the results are favorable for the use of Nickel-Titanium reinforcement rebars in order to reduce the abrupt form of fracture of reinforced concrete;
- the overall mechanical behavior of the system must be improved to acquire strength close to that of conventional steel.

4.1 Suggestions for future research

- Perform tests with mechanical treatment on the wire to provide better adhesion of the Nickel-Titanium surface to the concrete.
- Assess cyclic loading to take advantage of the displacement properties in the Nickel-Titanium reinforced system.

5 ACKNOWLEDGEMENT

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