Stress relaxation losses of prestressing steel wires

Prestressed structures are susceptible to relaxation losses which are of significant importance in structural design. After being manufactured, prestressing wires are coiled to make their storage and transportation easier. The possible deleterious effects of this operation on the stress relaxation behavior of prestressing steel wires are usually neglected, though it has been noticed by manufacturers and contractors that when relaxation tests are carried out after a long-time storage, on occasions relaxation losses are higher than those measured a short time after manufacturing. The influence of coiling on the relaxation losses is checked by means of experimental work and confirmed with a simple analytical model. The results show that some factors like initial residual stresses, excessively long-time storage or storage at high temperatures, can trigger or accentuate this damage. However, it is also shown that if the requirements of standards are fulfilled (minimum coiling diameters) these effects can be neglected.

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Active reinforcement is affected by stress losses due to relaxation, with this effect being of notable importance when designing prestressed concrete structures, since it can lead to a reduction on structural safety. In order to keep the influence of this effect under sensible values, it should be measured by means of standardized tests (ISO 15630-3 [1] and ASTM E328-86 [2]) and the results are required to meet the limits given in the standards. These measures are carried out on the wires immediately after being manufactured; then, the material is coiled and stored for periods of time that can be up to one year long.

Previous studies have been focused specially on the influence of temperature [3,4] on relaxation losses and also on the stabilizing treatment applied to reduce the residual stresses generated during the cold-drawing process [5,6]. Nevertheless, the effect of coiling and storage is usually neglected and no specific study on it has been found by the authors.
There is experimental evidence that, relaxation losses increase when wires are stored for long-time periods. In the authors' opinion, this is due to relaxation losses induced in the wire when this is coiled, which are responsible for the final curvature observed after uncoiling (Fig. 1).

Table 1: Minimum diameter of coil [7]

TYPE OF PRESTRESSING UNIT	MINIMUM DIAMETER OF COIL
Wires	225 x ϕ_{wire}
Strands (2 or 3 wires)	600mm
Strands (7 wires)	750mm

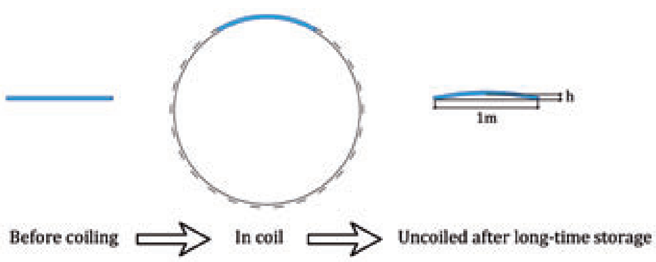

Figure 1: Sketch of the effect of the coiling-uncoiling process on a wire stored for a long-time period.

No specific reference to this phenomenon has been found in standards [7,8], nevertheless, limitations on the coiling diameter are given depending on the type and the dimensions of the wire (see Table 1). Although these limitations are intended to avoid excessive stresses in the cross section of the wire they can be sufficient for a local relaxation process to take place.
In addition to these limitations, some standards [7] recommend a practical check by measuring the sagitta h on a 1m long wire after uncoiling (Fig. 1).

In this paper, the effect of coiling and long-time storage on the relaxation losses is studied, with an explanation for the remaining curvature after long-time storage being sought. Three main factors are analyzed: coiling diameter, time of storage and residual stresses due to the manufacturing process. To assess the first two factors, an experimental programme is developed, where 7mm diameter cold-drawn wires are tested. Three coiling diameters are used, and the wires for each coiling diameter tested after uncoiling under two different stress ratios, one of 70% of the ultimate tensile strength (uts) and another one of 80% of the uts. The results obtained with the experimental program show the influence of coiling on the relaxation behavior of the material.

In addition to these tests, an analytical model is developed to simulate this problem. It is based on calculating stresses and strains for every step in the coiling-storing-uncoiling process, as well as the relaxation test carried out after it. The model is validated through comparison with the experimental tests described formerly.

Experimental programme

Mechanical properties of wires

For this research, wires manufactured by cold-drawing eutectoid steel rods of 12mm diameter by a commercial procedure were used. After six drawing passes the final diameter was 7.0mm.

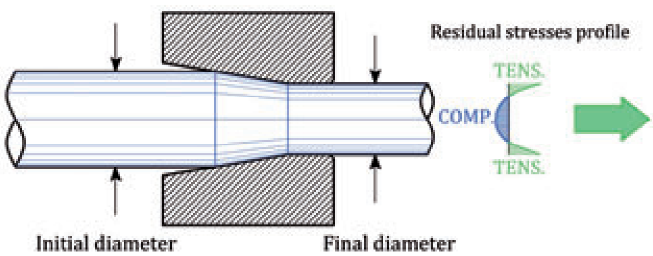

Figure 2: Sketch of a cold-drawing process

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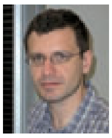

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This procedure generated residual stresses with tensile stresses on the surface [9] (see Fig. 2) that were relieved by means of a thermo-mechanical treatment, known as stabilizing [10].
Standard tensile tests were performed according to ISO 15630.3 [1] (the results are given in Table 2). Moreover, stress relaxation tests at different initial loads, according to ASTM E328 [2] were performed. (Fig. 3)

Coiling and uncoiling of wires

To test the influence of coiling diameters, two batches of wires were coiled at smaller diameters than those recommended by the standards [7,11] and another one at the minimum recommended diameter. All three batches remained coiled for 120 hours.
After uncoiling, the wires were no longer straight and displayed curvatures that could be fitted around circles of 500, 1000, and 9000 mm diameter.

Stress relaxation tests

Relaxation tests were performed at two different initial loads – 70 and 80% of the ultimate tensile stress (uts) – at room temperature and for up to 120 hours (Fig. 3). Results are shown in Table 3. Each figure is an average value of three tests.

Table 2: Material properties of the wires used in the tests

$\sigma_{0.1}$ (MPa)	$\sigma_{0.2}$ (MPa)	σ_{uts} (MPa)	ε_m (%)
1679	1704	1823	5.79

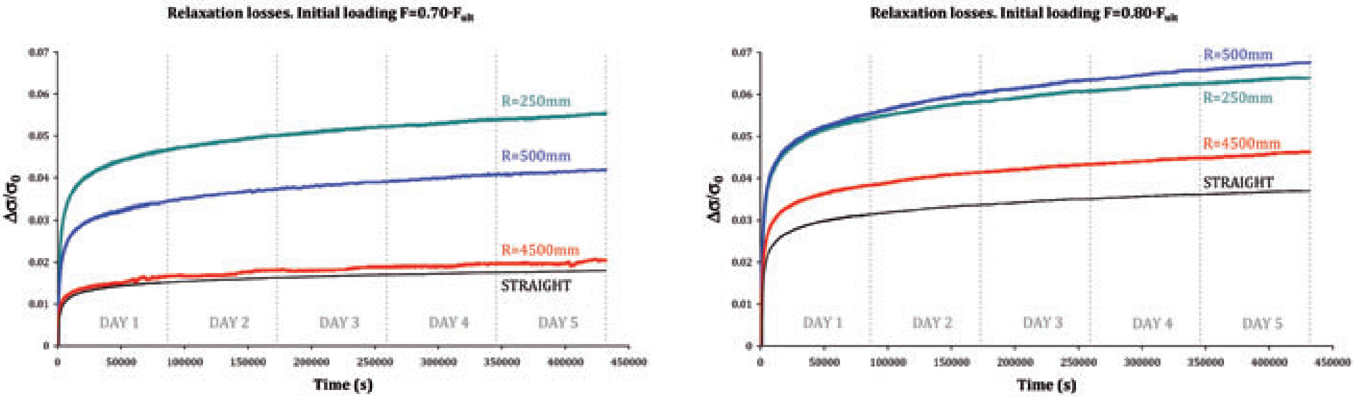

Figure 3: Relaxation losses in a 120-hour relaxation test for each of the coiling radius considered: a) Tests at 70% of the ultimate strength, b) Tests at 80% of the ultimate strength

Residual stresses

The remaining residual stresses after stabilizing were measured around the perimeter and along a diameter of the wire (see [5] for details). These measurements can be seen in Fig. 4.

Relaxation losses prediction

The purpose of this section is to provide a simple model that is able both to explain the experimental results and to predict the influence of coiling diameter, in addition to certain other parameters such as the storage time and the manufacturing induced residual stresses on the stress relaxation of steel wires.

Table 3: Relaxation losses for the different wires tested: comparison between the experimental values and the values obtained with the analytical model. These losses are expressed as percentages of the initial loading

Diameter uncoiled	TESTS: Relaxation losses F = 0.70 F_{ult} ($\Delta\sigma/\sigma_0$)	TESTS: Relaxation losses F = 0.80 F_{ult} ($\Delta\sigma/\sigma_0$)	MODEL: Relaxation losses F = 0.70 F_{ult} ($\Delta\sigma/\sigma_0$)	MODEL: Relaxation losses F = 0.80 F_{ult} ($\Delta\sigma/\sigma_0$)	Residual stresses* (MPa)	h (mm)
Straight	1.80%	3.70%	---	---	---	0
D = 9000mm	1.91%	4.64%	2.34%	4.35%	80	28
D = 1000mm	4.04%	6.75%	4.25%	6.73%	100	500
D = 500mm	5.44%	6.39%	5.96%	7.85%	120	---

* Average surface residual stresses
** The sagitta h is the distance shown and explained in Fig 1

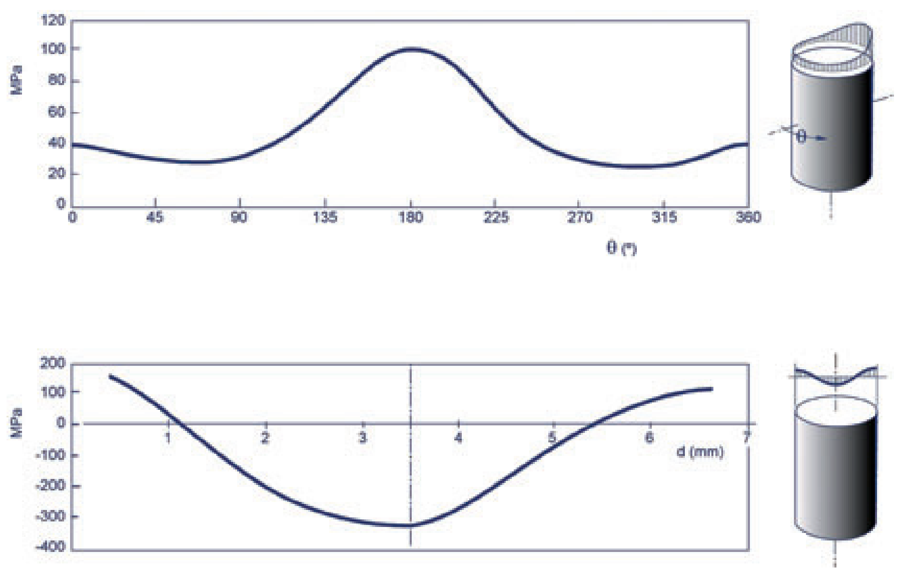

Figure 4: Residual stresses measured on the tested wire: top) Around the perimeter; bottom) Along a diameter.

An analytical model to study the influence of coiling

This model is based on Navier's hypothesis ('plane sections before loading, remain plane after loading') with the input data being the stress-strain curve of the material and the relaxation losses curve for different initial loadings (Fig. 5).

The evolution of the wire cross sectional stress profile during a coiling-storing-uncoiling process is shown in Fig. 6 and could be summarized as follows (for the sake of simplicity, no residual stresses are included).

- **Profile 0 –** Initial state: No stresses
- Profile 1 – After coiling, due to a bending moment: It is worth noting that stresses, in this example, remain below the yield stress.
- **Profile 2 –** After some time in coil: Tensile stresses relax, even in the elastic regime, according to Fig. 5. Due to this, the stress losses are inhomogeneous across the section of the wire and higher in the outer fibers.
- **Profile 3 –** After uncoiling: The stress profile is obtained by subtracting the above mentioned external moment to balance the corresponding loads. It should be noted that some stresses remain, although the whole stress profile is self-balanced. This is because the stress relaxation occurs in an inhomogeneous form throughout the cross section.
- **Profile 4 –** At the beginning of the relaxation test (at 0.70uts in this example). Due to the coiling-uncoiling operation, the stress distribution across the section at the beginning of the relaxation test is by no means uniform. The stress relaxation losses of the wire are the sum of the losses produced throughout the whole section. Note that some fibers are more loaded than 0.70uts and, hence, higher stress losses should be expected. Also,

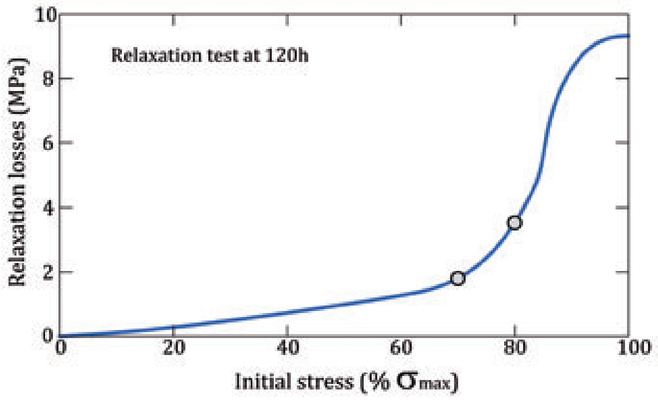

Figure 5: Behavior of a wire in a relaxation test under different initial loadings

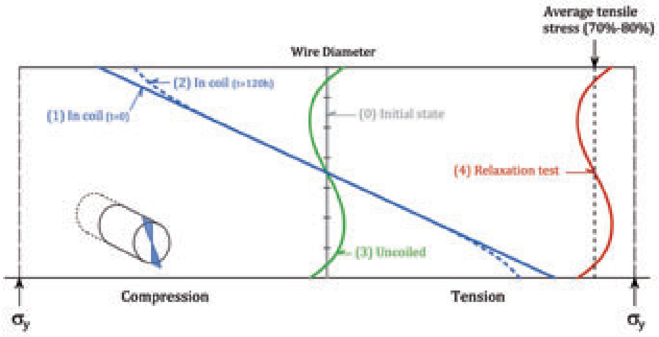

Figure 6: Stress profiles during the coiling-uncoiling process for a wire without initial residual stresses

some fibers are less loaded than 0.70uts but, as shown in Fig. 5, increases are more critical than decreases. The overall behavior is that after coiling-uncoiling wires exhibit relaxation losses higher than those of the wire before coiling.

Relaxation losses under different loadings

To obtain the behavior of the material for different initial loads (data needed in the model) in a 120h test (Fig. 5), only two experimental results were available (70% uts and 80% uts), the rest of the curve was estimated according to the work by Atienza and Elices [12].

The effect of the residual stresses

In the presence of initial residual stresses, remaining after the stabilizing treatment, a similar sequence of stress profiles is shown in Fig. 7. These residual stresses can emphasize the effects of coiling and, in some cases, could even produce the plastification of external fibers.

The effect of other factors

The effect of temperature

An increment of temperature produces an increase in stress relaxation losses, as examined by Rostásy [3,4] who has shown that even temperatures of about 40°C can lead to a significant increase in stress relaxation losses. Therefore storage temperature can have an effect on a relaxation test carried out after uncoiling. The authors have studied this factor [13] and have found that there is an influence of it on the final relaxation losses, though neglectable for temperatures of up to 40°C.

The effect of the time of storage

As the relaxation losses increase with time, excessively long-time storage can lead to higher relaxation losses. In fact, as a practical rule,

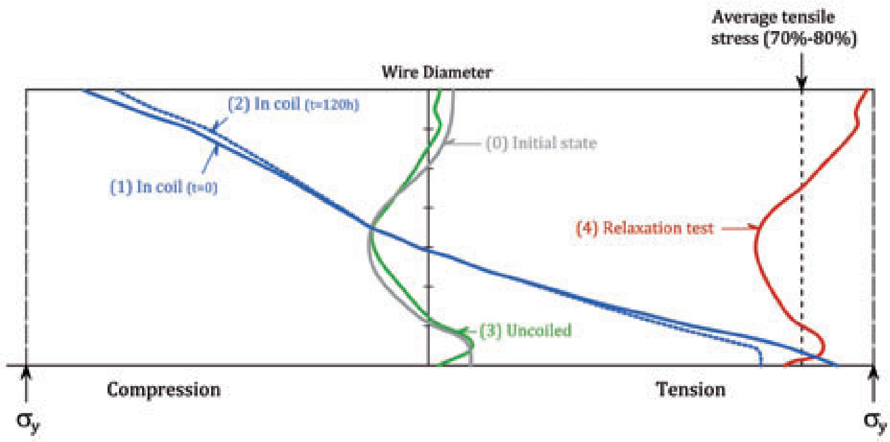

Figure 7: Stress profiles during the coiling-uncoiling process for a wire with initial residual stresses

some contractors generally avoid using wires that have been stored for periods longer than one year.

Comparison between the experimental results and those obtained by the analytical model

The predicted relaxation values are shown in Table 3 and compared with the measured ones. The agreement is satisfactory, considering the simplicity of the model. The results are particularly good when more realistic conditions are considered, such as for uncoiled final diameters of 9000 mm and 1000mm. The first one corresponds to a drum diameter of 1500mm, in accordance with recommendations, 225 times the wire diameter.

Conclusions

1. The experience of practitioners that coiling at small diameters can increase stress relaxation losses, has been successfully explained.
2. Residual stresses due to coiling represent an additional source of stress relaxation losses when the wire is loaded.
3. An analytical simple model is able to predict the evolution of stress relaxation losses after uncoiling and can be used as a guide when small diameters or high initial residual stresses are considered. The accuracy of the results can be improved by refining the model and the initial data.
4. The results of this work show that if the requirements of standards are met (minimum coiling diameters), the deleterious effects of coiling can be neglected. However, some other factors such as previous residual stresses, long-time storage or storage at temperatures higher than room temperature which are difficult to control, can trigger or accentuate this damage. In the authors' opinion measurement of this curvature prior to the final prestressing operations, in accordance with the requirements of some standards, is highly recommended, since it gives a more precise idea of the relaxation losses taking place after coiling and a long-time storage than the simple measurement of the coiling drum diameter.

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20 years of Syspro

Now with EPD for precast concrete

Syspro-Gruppe Betonbauteile eV is now 20 years old. It is an association of innovative companies in the precast concrete industry forming a quality community. Originally, the primary purpose of this organization was to exchange experience of automated circulation systems - which were then new to the market – in the field of precast concrete production. Eleven manufacturers were founder members, eight of which still belong in 2011.

With the introduction of the HiQ seal of approval in the 1990's, the group took on a demanding self-imposed obligation by deciding to constantly update and refine its guidelines. Most recently, as of 2012, the prerequisites for Environmental Product Declarations (EPDs) will be incorporated into the association's certification system. The individual plants will submit EPDs for precast walls by the end of 2011, followed by EPDs for precast flooring in 2012.

Just as the group was celebrating its tenth anniversary, the building authority for double walls with core insulation - thermal walls - was granted to it. Today, thermal walls are a well proven and seminal component of the group's product portfolio. As Syspro Chairman Joachim Look states, this product "is fully consistent with the current environmental and energy policy development in our countries."

In recent years, the community has focused increasingly on developing technical information. The publications "The technology behind the ceiling" and "The technology behind the wall" appeared in 2006 and have become standard works on building with precast flooring, element walls and thermal walls. Since the beginning of 2011, architects can download creative and constructive suggestions from the document "Betonfassaden im Thermowand-System" (Concrete facades in the thermal wall system).

New member

Progress AG "Bauen mit System", based in Brixen, South Tyrol, was accepted as the 15th member of the Syspro-Gruppe Betonbauteile eV in October 2011. The new member belongs to the Progress group, which operates a precast production facility for the construction industry in Northern Italy.

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