



HAL
open science

Mechanical impact of wires break in grouted external prestressing tendon

Jonas Aparicio, Tien Hoang, Gwendal Cumunel, Gilles Forêt, Yannick Jeanjean, Julien Castres Saint Martin

► To cite this version:

Jonas Aparicio, Tien Hoang, Gwendal Cumunel, Gilles Forêt, Yannick Jeanjean, et al.. Mechanical impact of wires break in grouted external prestressing tendon. Academic Journal of Civil Engineering, 2023, 10.26168/ajce.41.1.33 . hal-04248433

HAL Id: hal-04248433

<https://enpc.hal.science/hal-04248433v1>

Submitted on 19 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Mechanical impact of wires break in grouted external prestressing tendon

Jonas Aparicio¹, Tien Hoang¹, Gwendal Cumunel¹, Gilles Foret¹, Yannick Jeanjean², Julien Castres Saint Martin²

¹ Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France

² Sanef, Issy les Moulineaux, France

Corresponding author: J. Aparicio (e-mail: jonas.aparicio@enpc.fr)

ABSTRACT External prestressing is a construction technique widely used since the 1980s for large civil engineering structures to reduce the cross-sectional area of structures and thus their permanent load, and more recently to reinforce structures. External prestressing tendons are composed of strands, each comprising 7 wires with a very high elastic limit, laid in a HDPE sheath, anchored in reinforced concrete blocks and generally tensioned to 80% (excluding creep and shrinkage) of their ultimate tensile strength. To protect the cables, cement grout was injected into the sheaths until the 2000s. However, this protection system does not preserve the cables in the event of a sheath failure (leakage, injuries, etc.) which compromises its watertightness and causes issues with the quality of the injection. The durability of the cable is therefore no longer guaranteed and stress corrosion occurs. When the wires and strands re-anchor by friction in the grout after breaking due to corrosion, the stress of the remaining of the tendon increases until the breaking load of the whole tendon is reached. The break is then very sudden, releasing considerable energy that can endanger the structure and any operators present on site.

Knowledge of the state of the cable at a given level of degradation and the permissible degradation before it breaks is therefore of prime importance to the managers of the structures.

Several 46m long cables between supports were tested using the cable traction bench of the Gustave Eiffel University in Nantes and brought to failure by progressive cutting of the wires composing the strands. Firstly, three tendon comprising a single strand of seven wires were tested, followed by two tendon comprising five strands. The tendons were tensioned to 70% of their breaking load corresponding to the usual stress level observed in the tendons of real structures having subjected to shrinkage and creep phenomena.

The experiments conducted and the analysis of the results have provided a better understanding of the evolution of the tension in the tendon when it is damaged. For this purpose, a model was developed which allows to obtain an estimate of the length affected by the rupture of wires (transfer length) and this work brings some results concerning the transfer of stresses in the tendon and strands caused by these ruptures.

Keywords Prestress loss, Wire break, Seven-wire strand, Interwire friction, Posttensioned bridge

I. INTRODUCTION

Prestressing concrete is widely used on long-spanned bridges as it is an efficient method for reducing structural mass and improving integrity. This paper focus on prestressing tendon made of strands of steel wires laid in a plastic sheath then grouted. The strands in this paper each consist of one straight core wire layered by six helical wires. The strands are put to a tension of about 70% of their fracture strength which is the usual remaining tension in prestressing tendon after creep and relaxation. The strands are protected against

exterior aggression by a plastic sheath mostly HDPE. The sheath was injected with grout to protect the steel from corrosion until the 2000s and is now injected with wax or fat. Issues during construction or exploitation can lead to loss of protection and steel corrosion. Loss of wire due to corrosion is the main durability issue of prestressing tendon Godart (2014). Wire breaking leads to stress redistribution due to friction of a wire with the grout and the other wires. A cut wire will get its original tension back at a distance from the cut. That distance is called re-anchoring or transfer length. It can lead to catastrophic tendon breaking as individual wires reach fracture strength leading to a cascade of breaking. Tendon breaking occurs after around 30% of section loss. This is the section loss where remaining steel surface is not sufficient to endure the remaining tension, thus causing the tendon to break. Damaged tendons usually show wire breaks distributed on multiple strands.

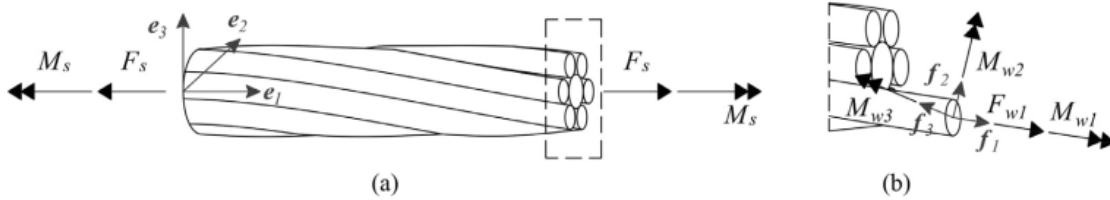


Fig. 2. (a) Straight strand subjected to axial-torsional loads. (b) Generalized stresses on the wire cross section.

FIGURE 1. Force and moment generalised on the strand and on a helical wire extracted from Foti & Martinelli (2019)

Behaviour of damaged tendon were previously thought to behave with the strand re-anchoring phenomenon. When a strand breaks, if there is sufficient bond between the strand and the surrounding concrete and that the tendon is sufficiently long, the strand will get back to its original stress a distance to the break. This distance is called transfer, transmission, re-anchoring or anchorage length depending on the papers. This damage model keep the symmetry of the strand and the phenomenon is well understood as it is central to how stress is transferred from the strand to the concrete in internal prestressing. The Poisson effect cause the ruptured end of the broken strand to form a wedge and create friction with the grout. Furthermore, the loss of tension in the wires cause the wire to unfold and thus increase contact with the concrete, this is called the Hoyer effect (Briere et al. (2013)). Hoyer and Poisson effect combine to create friction between the wires and between external wire and the grout which cause stress to be transferred back in the cut strand. Abdelatif et al. (2017) show that the transfer length for a grouted strand is of the order of a meter in a review of different studies about this phenomenon. The mechanical characteristic of steel and concrete are shown to be the main parameter influencing the re-anchoring length. A sensibility analysis can be found on the article Watanabe et al. (2011) following an experimental campaign of cutting strand in different configuration. The article Asp et al. (2021) shows that in case of inefficient grouting the transfer length will grow bigger, with 1.7m with incomplete grouting to 1m with good grouting. The re-anchoring of a whole strand is presented in multiple construction codes such as American Concrete Institute 2011, the Eurocode EN-1992-1-1(2004) (§8.10.2), and the British code CS 455 (§8.3.1). According to codes, the transfer length of a cut strand is of the order of 1 meter. Detected damage on tendon show that damage occurs on a wire by wire basis with damaged strand often breaking only after multiple wires have already ruptured.

The response of a undamaged strand subjected to tension and couple has been explored in numerous papers, reviewed by Ghoreishi et al. (2007) where steel wires are modeled as Love thin rod and interaction

between wire are expressed in the helical Fresnet coordinate system (Figure 1). The articles reviewed differ about how they solve contact, model traction or take into account Poisson Effect and wire flattening but they all rely on symmetry which makes them no longer valid for damaged strand which has seen less theoretical and experimental works.

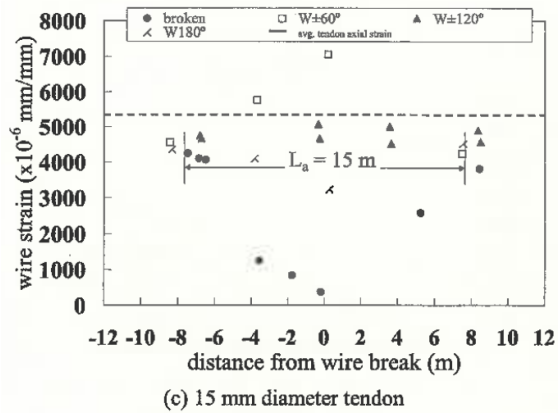


Fig. 10—Outer wire strains for tendons with single broken wire.

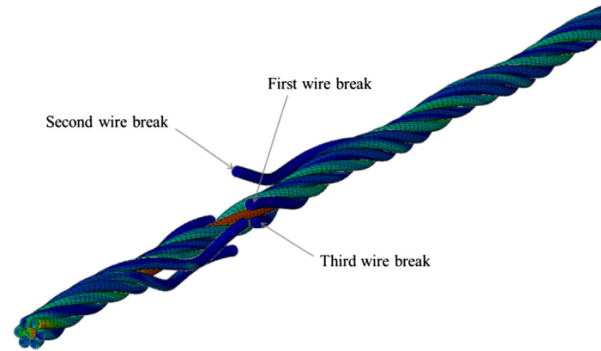


Fig. 21. Multiple wire breaks.

FIGURE 2a. Strain distribution in a strand with a broken wire extracted from MacDougall & Bartlett (2003) **FIGURE 2b. Numerical model of a strand with wires breaks extracted from Abdullah et al. (2016)**

There are fewer studies about the breaking of individual wire. MacDougall & Bartlett (2003) investigated the re-anchoring of one or two wire in a strand. Cutting of individual wire in a strand with a concrete deviation lead to transfer length of more than 10 meters. The transfer is partial as tension in the strand go down by 2-4% each cut, in a 7 wire strand each wire account for around 14% of the tension. This paper shows that stress redistribution in the wires is symmetric but not homogeneous. Tension after the cut in each wires depends on its relative position to the cut wire (Figure 2a). Beltrán et al. (2018) use analytical and FE computation to derive the static response of a strand with a broken wire, the strand is unbounded. Both of this article assume that damage of broken wire induce a helical displacement of the strand to respect equilibrium. A tentative confinement has been done on the The numerical and experimental study conducted by Abdullah et al. (2016) (Figure 2b) with unstressed strands surrounding the stressed strand in which wires are cut. Prestress loss is only 10% less with the confinement than without. Stress transfer is worse than in MacDougall deviated strand. Transfer length has been measured as the 30 meters between the cut and the end of the bench.

The review has shown that while the behaviour of the healthy strand is well known, the behaviour of a damage strand is only partially understood and there are no study on the behaviour of damaged strands with a confinement as strong as the one in grouted external prestressing tendon and neither with force transfer due to wire damage between multiple strand to the best of the authors knowledge. This behaviour is useful in order to better the assessment the remaining capability of a detected damaged tendon. Furthermore, the improved knowledge on a damaged tendon could be use to improve control and detection of default in the tendon.

In this paper, an experiment is presented which was to build realistically sized tendons then break them by cutting wires one at a time. The aim of this experiment is to better the understanding of stress transfer inside the damage tendon and to have an estimation of the length affected by the damage. The experiments has been repeated using variable number of strand, brittleness of sheath and cutting schedule in order to

perform a sensibility analysis on these different parameter. Mechanical results has been obtained from a cell force, photograph and film.

II. EXPERIMENTS

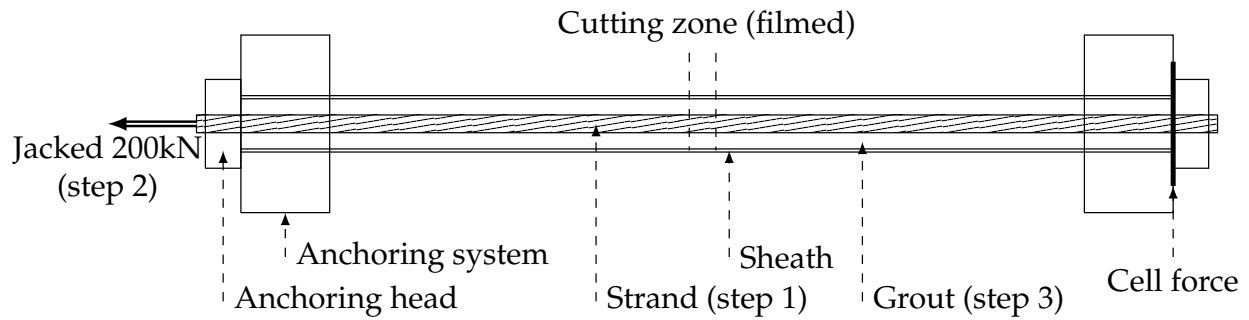


FIGURE 3. Sketch of the experimental set-up for a tendon with one strand

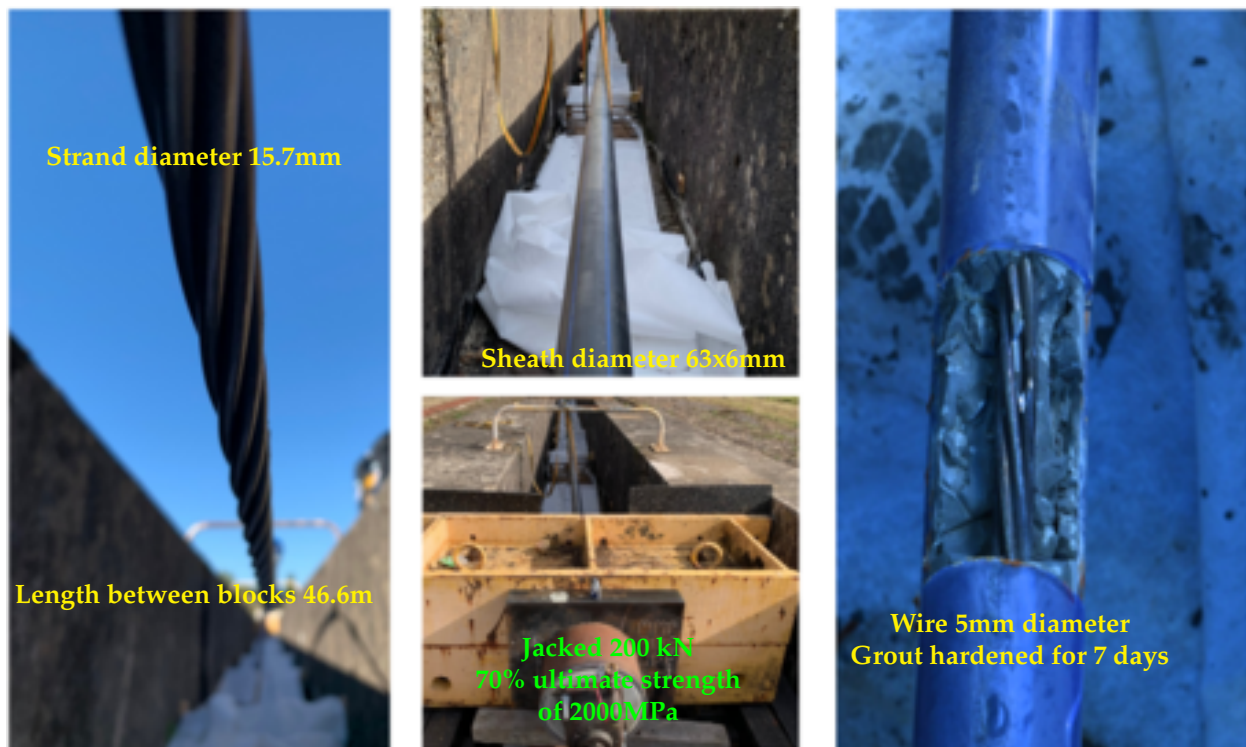


FIGURE 4. Photos of the experimental bench at various step of the experiment set up

This experiment was funded by the ASFA (Association des Sociétés Française d’Autoroute) to further the understanding of the remaining capabilities of damaged tendon. The experiment had been made at Gustave Eiffel University Nantes (UGE) on the 200m experimental bench of the Material and structure Department (MAST). The installation (Figure 4) was carried out by the Freyssinet company. Three tendons containing one strand each and two with 5 strands each were tested. The strands were passed through the anchoring system (step 1 on Figure 3) and then through the HDPE sheath (63x5.8mm), whose segments are

welded together. In the first two experiments, the center part of the sheath was made of transparent PVC to allow visually following of the crack propagation in the grout, with the PVC and HDPE sheath connected by a screw joint. A grouting vent was provided for better grouting quality. Anchoring systems were installed at both ends with a force cell at the passive end. Tension was applied with a hydraulic jack at the active end at 70% of the tendon's braking strength (step 2 on Figure 3). The tendon was then injected with Holcim Superstresscem grout, which is widely used for this type of application (step 3 on Figure 3). The 5 tendons had a length of 46.6 m between the two anchor blocks. After allowing the grout to sit for 7 days, a 20-cm trapdoor was made in the sheath to access the wire and the grout was removed in the trapdoor so that the wires could be cut one by one with a Dremel mini rotary saw during testing (Figure 5).

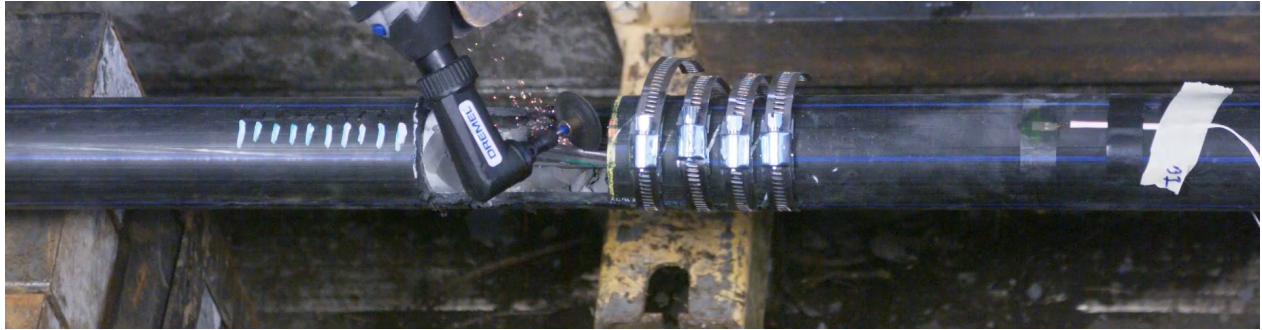


FIGURE 5.a Second cut of the third mono strand

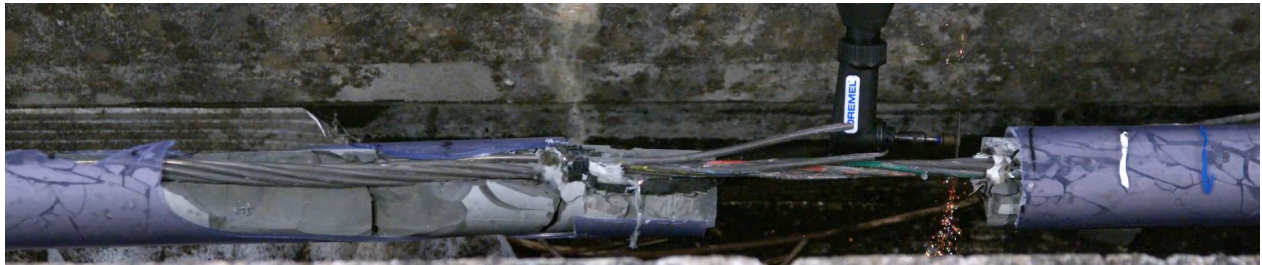


FIGURE 5.b Third cut of the thirist mono strand

FIGURE 5. Photos of cutting

Great precautions were taken to protect the operators and in particular the operator in charge of cutting the wires by taking care to protect him from whiplash effect of the tendon during its rupture. Many instrumentation systems have been installed on the tendon by different teams. This article focuses on the results obtained using a high frequency camera, the force cell and photograph of the central trapdoor.

III. RESULTS

TABLE 1. List of experiments

Strand	Sheath	Initial tension	Theoretical/Experimental wire loss needed for the rupture	Others
1T15	PVC	186 kN	3/6 (43%/86%)	Brittle sheath
1T15	PVC	204 kN	3/7 (43%/100%)	Brittle sheath
1T15	HDPE	204 kN	3/4 (43%/57%)	
5T15	HDPE	1018 kN	10/16 (29%/46%)	Sequential cutting
5T15	HDPE	988 kN	12/15 (34%/43%)	Alternate cutting

The tension in the tendon decrease over the course of the experiment. It shows that stress transfer is incomplete. Due to the loss of tension, the number of wires cut until the tendon rupture will be greater than the number that would have to be done for the tendon for to reach its tensile limit, assuming that the tension in intact wires is uniform (Table 1). The tensile limit of the steel is 1.96GPa according to the certificate given by the strand manufacturer. Most of the stress that is in a wire is transferred when this wire is cut as tension loss is only of a few kiloNewtons while each wire hold initially a tension on the order of 25-30kN. However, in cases where the grout is severely damaged (see Figure 4b) or when an entire strand is broken (Square in Figure 6a), the tension loss can be much higher, exceeding the value of 30kN.

A. *Sensibility analysis on the quality of stress transfer according to the confinement and schedule of cutting*

When a wire is cut, some of the tension it was carrying is lost and some is transferred to other wires in the tendon. Furthermore, the transfer in the sheath and grout is not taken into account because they were removed to perform the cutting of the threads. However, this is unlikely to introduce a significant bias because the tensile strength of the grout and the stiffness of the sheath are very low compared to those of the steel. The stress transfer efficiency then appears to be directly correlated to the bond between the wires and the grout. When the confinement of the steel decreases due to excessive damage to the grout, the stress transfer decreases to almost zero (Figure 6a). Sheath failure, which occurs with the brittle PVC sheath in the first two experiments, causes the grout to rupture and the strand and grout to split over a distance of several meters (Figure 4b). In general, grout degradation due to multiple ruptures tends to make stress transfer less and less efficient as damage increases in the tendon (Figure 6a and 6b).

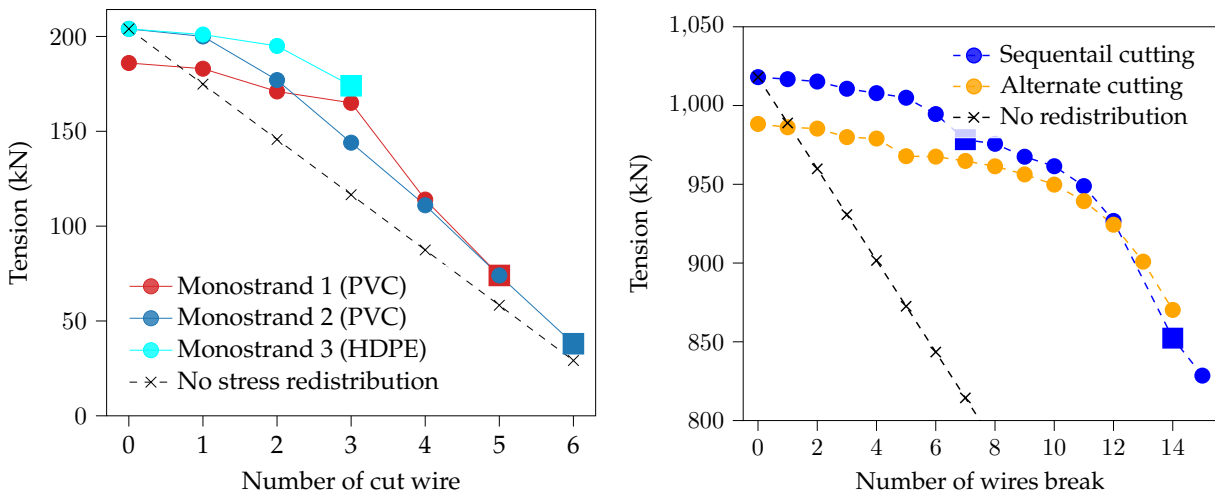


FIGURE 6a. Tension in the monostrand according to the number of wire cut

FIGURE 6b. Tension in the 5T15 according to the number of wires broken

Monostrand The experiment display two different behaviours for monostrands depending of the sheath used. On the one hand, when a PVC sheath is used for the first two strands, the wire breaks cause the sheath to rupture followed by large cracks in the grout. There is then a loss of bond between the grout and the tendon over a length that increases with each cut. When the tendon is debonded from the grout, which occurs at the 4th cut for monostrand 1 and at the 2nd cut for monostrand 2, each cut causes the tension in the tendon to drop by a value only slightly less than the initial tension of the cut wire, showing that the tension transfer during wire cutting is minimal, with most of the tension lost (Figure 6a).

On the other hand, when a HDPE sheath is used, only small cracks are observed on the grout which reflects the fact that the bond between the grout and the strand is not affected. Tension loss is only a small fraction of the cut wire tension. Most of the tension from the cut wire is distributed to the other wires. As the grout and sheath continuity has been cut in order to free access to the strand, the cut wire tension is transferred to the others wires.

The relationship between bond strength and confinement is coherent with the slip pip test made by Hyett et al. (1992) which show that the materials used for sheath (Steel, PVC, Aluminium, Heat shrink) has prime importance on bond strength of cable bolt. Pull-out test results should be treated with caution as Hoyer and Poisson effect will cause adherence to go down in pull-out tests and up in re-anchoring.

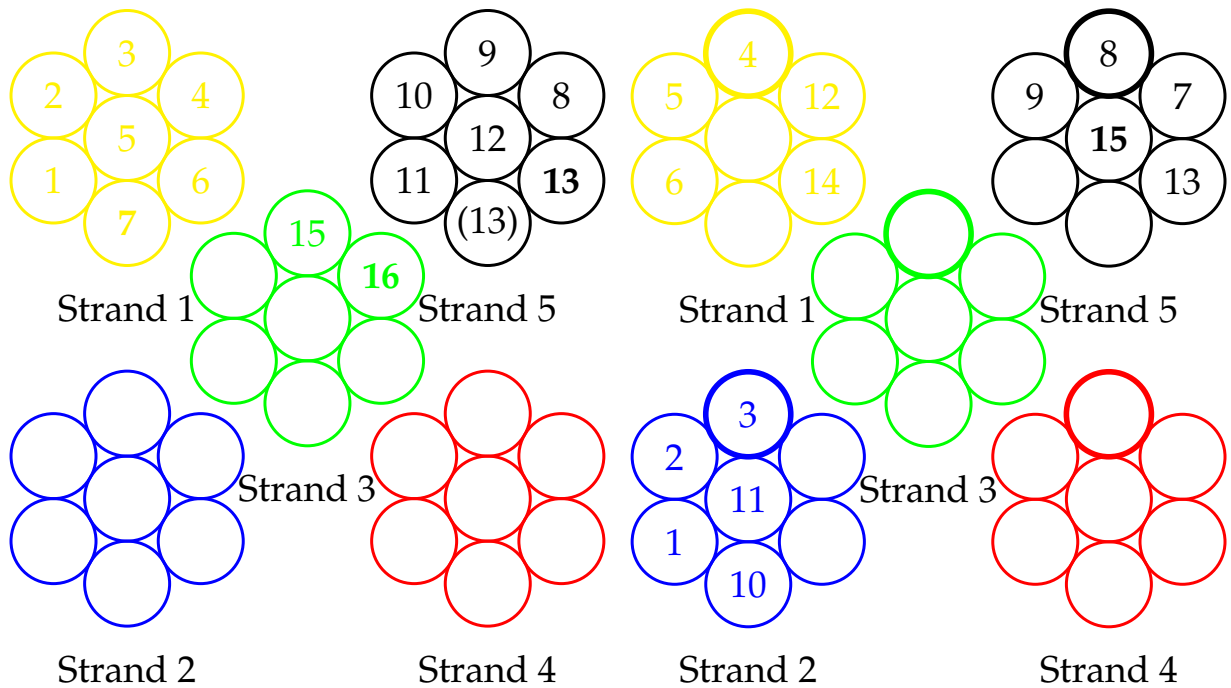


FIGURE 7a. Sequential cutting schedule

FIGURE 7b. Alternate cutting schedule

Tendon with multiple strands Two experiments has been made on tendon with 5 strands each. Using two different schedule for the cut.

In the first one, wires were cut in the same strand until the strand break before cutting wires in another strand. This was called the sequential cutting (Figure 7a). The second strand broke on the sixth cut on this strand (in total the thirteenth), with the entire tendon breaking on the second cut in the third strand. In the second, one wire was cut on 3 different strands. The original plan was to cut 3 wires on each strand, then 2 and finally 1. But accessibility constraints made it impossible to access some wires and an adjustment had to be made as a last resort (Figure 7b). There is little tension loss at each cut until the very end albeit tension loss of individual cut tends to get bigger as the damage of the tendon increase and when a strand finally breaks. There is strong evidence suggesting that stress of the cut wire is not only redistributed in the strand which it belongs but also in the others strands. Sequential cutting see failure of strand after 6 and 7 cuts. Failure would have occurred earlier if stress was only redistributed in the strand being cut. But the redistribution of the tension is not homogeneous in the strands. The high-frequency film of the rupture of the tendon subjected to alternative cutting shows that the outer 4 strands fail before the central one, even

though only 3 of the outer strands were cut.

TABLE 2. Impact of grout bond and geometry of damage

Tendon	Grout bond	Tension loss	strand breaking
Monostrand	Bad	Important	6-7 wires cut
Monostrand	Good	Small	4 wires cut
5 strands (seq)	Good	Small	6-7 wires cut
5 strands (alt)	Good	Small	Not until the tendon breaks

Which lead to the four following categories

1. Monostrands with a weak confinement. The weak confinement lead to the failure of the bond. Most of the stress in the cut wires is then lost rather than transferred. 6 to 7 cuts are needed to break the strand as tension decreases at each cut by a amount close to the tension in the cut wire. In the experiment monostrand 1 and 2.
2. Monostrand with a strong confinement. The holding of the bond leads to a good stress transfer with very little tension loss. The number of cuts that was needed to break the tendon is 4 instead of 3 if no stress were lost. In the experiment monostrand 3.
3. Multiple strand when strands are cut wire by wire sequentially. There is little loss of tension. Strand need the cutting of 6 to 7 wires to break which show that an important share of the stress is transferred in the others strands.
4. Multiple strand when wire breaks are distributed over several strands while not allowing strands to break. There is little loss of tension. The strand can hold with only two wires remaining, showing that the tension of the cut wires is transferred into the other strands. The kinematics of the break with the outer wire breaking before the center wire shows that the tension distribution is not homogeneous in the strands with the outer strands, even intact, more impacted.

The experiment from Abdullah et al. (2016) shows that when a strand is unbounded tension fall after a cut by the value of tension that was in a wire. When the strand is bounded by other strand, there is a small transfer, close to the result of the first category when bond is weak but with no degradation of bond. Tension loss were probably bigger in our experiments than on the field due to the need of cutting a windows to reach the strands. The authors argue that depending of bond quality, the strand will go to perfect stress transfer to no stress transfer, the tension of the cut wire is lost if the strand is totally unbounded. The bond depends of grouting quality and sheath quality, as the breaking of the sheath will cause the grout to break regardless of its quality due to the bad traction resistance of grout. No tendon with multiple tendon and poor bond was tester but it would have probably lead to close to no stress redistribution and each individual strand would act follow the first category.

There is uncertainty about the exact value of stress transfered and tension loss at each wire cut that will translate into an uncertainty about the number of wire loss that will cause the tendon to break. This is because this transfer depends on stong dynamic effect, the cracking of the grout, the exact position of the wire and the relative position of every other wires, in a real tendon the dispersion of tension between the tendon. This will lead to a small discrepency of result even trough the experiments done show the first two monostrand and the two tendon with 5T15 having close behaviour, eventhrough the 5T15 was submitted to two very different cutting schedule (Figures 6a and 6b).

B. Estimation of transfer length using sliding of the wire

The transfer length is the distance to the cut where the impact of the cut has vanished. The following section introduce a model which gives an estimation on the transfer length based on the measurement of the sliding of the wire that has occurred after the cut. This sliding is due to the relaxation of the strain of the cut wire.

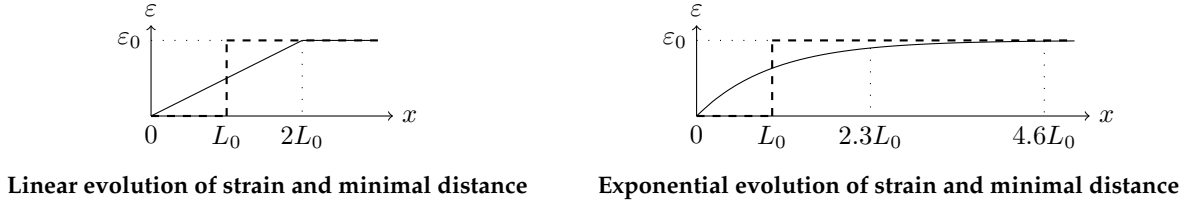


FIGURE 8. Strain in the cut wire according to the distance to the cut

Let g the sliding of a cut wire *i. e.* the distance between the two cut end and x_c the distance to the cut end. The strain is assumed to be symmetric according to the cut thus sliding on each side is $\frac{g}{2}$. The transfer length will be defined as the distance were the strain in the wire would stop its variation. This model is purely cinematic. Strain variation is assumed monotonous. Different expressions can be selected for strain. The strain in each helical wire is $\cos^2 \alpha \varepsilon$ (Foti & Martinelli (2019)) with ε being the deformation along the axis of the strand $\frac{\Delta L}{L}$. A length l on the strand translate into a length $l / \cos^2 \alpha$ on the helical wire due to the curvature of the wire, with α being the lay angle of the helyx which is 7.8° for the experiment.

The model does not take into consideration the rotation of the strand. Assuming symmetry of the strain and L_h being the length from the cut to the anchoring, the sliding would be

$$\frac{g}{2} = \int_0^{L_h} \delta\varepsilon(x_c) dx_c = \int_0^{L_h} \varepsilon_0 - \varepsilon(x_c) dx_c \quad (1)$$

with $\delta\varepsilon(x_c)$ being the variation of the strain, projected on the axis of the strand, due to the cutting. On the x_c axis 0 being the position of the cut end and L_h the axial distance between the cut on the position of the anchorage. Let ε_0 the generalised strain in the strand far from the cut where the strain has converged. It is also the original strain of the strand computed with the ratio of displacement of the strand to length of the strand. It is assume that ε_0 is constant which is valid only when tension loss is very small compared to the tension of the tendon and if wire tension is homogeneous far from the cut. Both assumption would become problematic as the number of cut grow. The smallest transfer length that account for the sliding is $L_0 = \frac{g}{2\varepsilon_0}$ (dashed curve Figure 8) assuming strain monotonous, non-negative and of value ε_0 far from the cut. It is achieve with

$$\varepsilon(x_c) = \begin{cases} 0 & \text{if } x_c < L_0 \\ \varepsilon_0 & \text{if } x_c \geq L_0 \end{cases} \quad (2)$$

With the assumption of a linear evolution of the strain from 0 to ε_0 the strain after the transfer length then the transfer length is $2L_0$ (left solid curve Figure 8)

$$\varepsilon(x_c) = \begin{cases} \frac{x_c}{2L_0} & \text{if } x_c < 2L_0 \\ \varepsilon_0 & \text{if } x_c \geq 2L_0 \end{cases} \quad (3)$$

If exponential evolution of the strain is assumed. Which would be the result of a very simple model assuming exponential friction between the cut wire and central wire. Which is achieved by introducing a Coulomb friction law in the model where friction force between the wires depends of contact force in the wires which

is dominated by the tension. Then the evolution of the strain with the distance to the cut is (right solid curve Figure 8).

$$\varepsilon(x_c) = \varepsilon_0(1 - e^{-\frac{x_c}{L_0}}) \quad (4)$$

With exponential evolution of the strain, the wire get backs to 90 % of its strain at a distance to the cut of $2.3L_0$ and 99% at $4.6L_0$. The table 3 shows the relation between sliding and transfer length with a generalised strain assumed to be $7mm/m$, the strain created in the strand by having a tension of 70% of the tensile strength.

TABLE 3. Sliding and transfer length for $\varepsilon_0 = 7mm/m$

Damage	Typical sliding	Transfer length			
		Minimal	Linear	Exp (90% strain)	Exp (99% strain)
1-2 wire cut	1cm	1.4m	2.8m	3.2m	6.4m
4-5 wires cut	5cm	7m	14m	16m	32.2m
1 strand cut	10cm	14m	28m	32.2m	64.4m

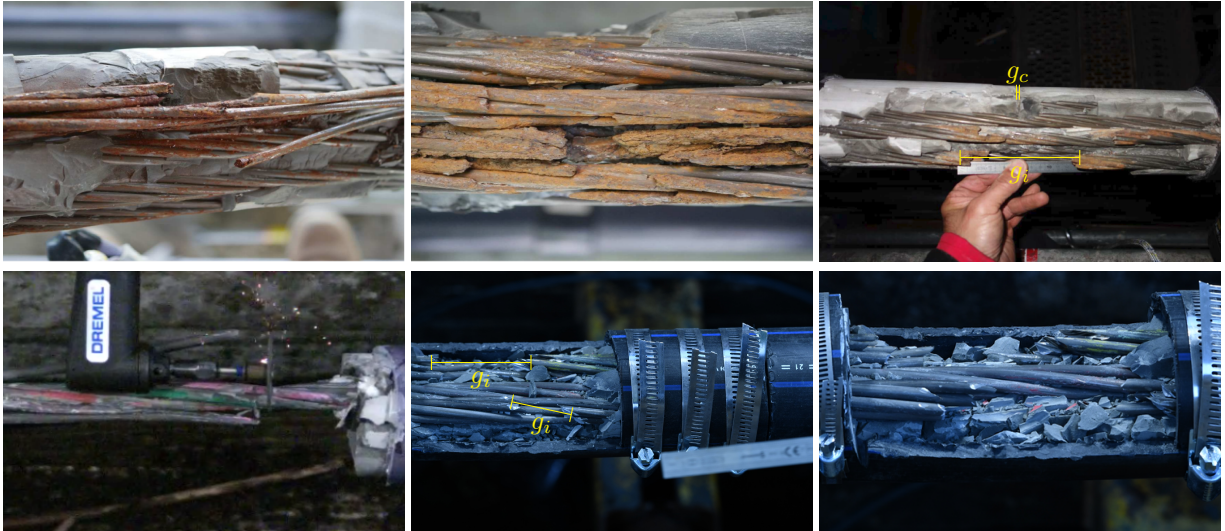


FIGURE 9. Up photos of damage on opened tendon on a bridge © IFFSTAR for Sanef. Down photos of broken wire during the experiments

Figure 9 shows different degree of damage on site and during the experiment. Sliding depends on the state of the tendon, with sliding bigger when whole strand are cut. It can be hard to distinguish displacement due to sliding and loss of mater due to dissolution cause by corrosion.

Computation of a upper bound of the remaining prestress strength due to sliding Sliding on the wire were estimated using photo and video of the experiment.

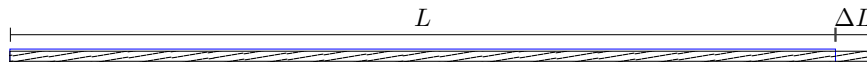


FIGURE 10. Reference (blue) and deformed (black) configuration of the strand

Let $\varepsilon_i(x)$ is the longitudinal strain of a wire, i from 1 to the number of wire N_{wire} and $\varepsilon_g(x)$ for the grout (Figure 9), where x is the position on the tendon. The contribution of the sheath to the tension is insignificant

due to very low Young modulus. L is the total length of the tendon in the reference configuration before jacking with x such as $0 \leq x \leq L$ represent the whole length. The extension of a tendon is given by (Figure 10)

$$\Delta L = \int_0^L \varepsilon(x) dx \quad (5)$$

This extension is initially, before any cutting occur ΔL_0 . Because the two ends of the tendon are fixed, the sliding length of each cut wire is calculated by

$$\Delta L_0 = g_i + \int_0^L \varepsilon_i(x) dx \quad (6)$$

$$g_i = \Delta L_0 - \int_0^L \varepsilon_i(x) dx \quad (7)$$

The loss of tension can be written as

$$\sum_i E_i S_i g_i = \Delta L_0 \sum_i E_i S_i - \int_0^L \sum_i E_i S_i \varepsilon_i(x) dx \quad (8)$$

where S_i is the section of the wire and ΔL_0 the initial elongation of the strands. The tension T can be written depending of the strain

$$T = \sum_i E_i S_i \varepsilon_i(x) + E_g S_g \varepsilon(x)_g$$

with the initial tension T_0 being

$$T_0 = \frac{\Delta L_0}{L} \sum_i E_i S_i$$

Thus,

$$\sum_i E_i S_i g_i = L(T_0 - T) = L\Delta T \quad (9)$$

The aforementioned equations can be written as follow

$$\Delta T = \frac{E_g S_g g_g + E_s \sum_i S_i g_i}{L} \quad (10)$$

where E_g, E_s are the Young's modulus of the grout and the steel, S_g, S_i and g_g, g_i are the section and the sliding length of the grout and the cut wire i .

At each cut, a new wire slide and sliding of the already cut wires increase. This phenomenon account for the quasi-quadratic evolution of the total tension loss (ΔT_n) for the first few cut (Figure 11). There is no estimation for the 5T15 with alternate cutting schedule as the angle of the camera during this experiment makes it very hard to get an estimation of the sliding with the chosen precision. Figure 11 shows the comparison between measured tension loss ΔT_n and estimated tension loss due to sliding according to the number of cut n . The sliding of the grout was not used for the estimation as the grout broke and fell into the bench during the experiment. It leads to an underestimation of the tension loss, which makes it conservative. The error bar is done assuming sliding is known ± 1 cm. This uncertainty is due to the measurement of sliding done using photo of the tendon and having to account to angle of view effect and inaccuracy due to end of some wires being out of the field of view, hidden by the strand or the sheath. The sliding has to be extrapolated using the wires where the two end are visible. Only sliding of the wire is considered as sliding of the grout can't be measured on the two monostrand due to grout breaking and falling into the bench. The loss of tension due to rotation is not considered in the model. As rotation is not permitted during tension,

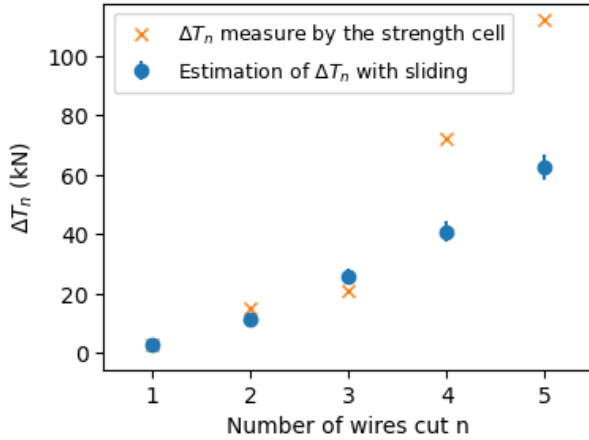


FIGURE 11.a Monostrand 1

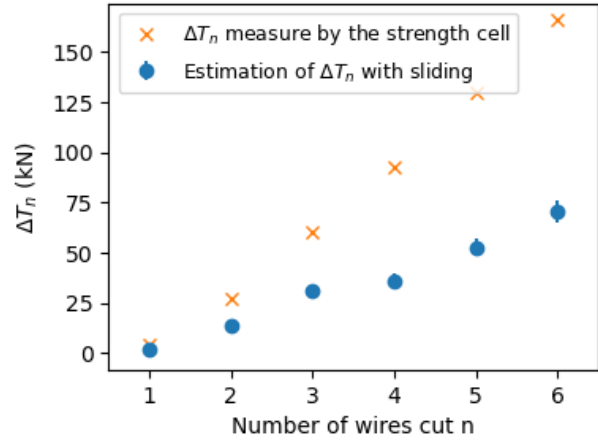


FIGURE 11.a Monostrand 2

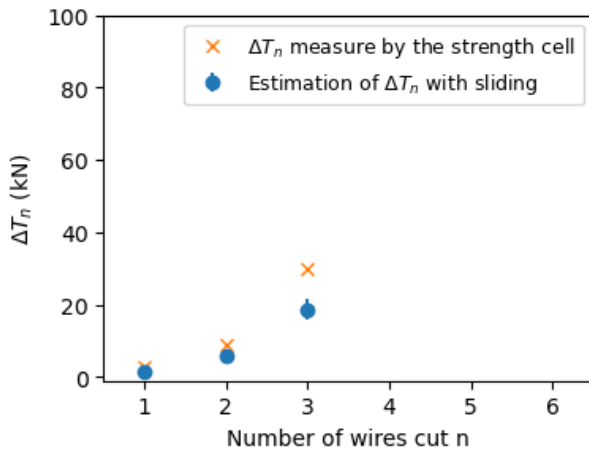


FIGURE 11.a Monostrand 3

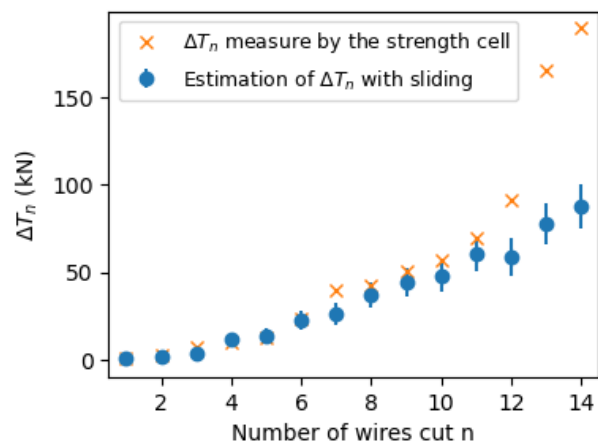


FIGURE 11.a Sequential

FIGURE 11. Comparison tension loss measured by the sensor and estimated with sliding

an important torque is created in the strand (see Ghoreishi et al. (2007) for models linking elongation to torque). As damage of the strand cause relaxation of the torque, a twist is created on both side of the strand. This twist will cause the tension in the strand to further decrease. The transfer of tension to the grout and the loss of tension due to the freeing of strand rotation are supposed to be responsible for the difference between the model and loss of tension measured by the strength cell.

IV. CONCLUSION

An experimental campaign has been done on multiple prestressing tendon in order to enhanced the understanding of damage mechanism. With the results of this campaign impact of grouting, multiplicity of strands and wire breaking influence on the behaviour of a damage tendon has been explored. Tension has been shown to conserve with damage because of the bond between the strand and the grout. When this bond fail, it cause most of the tension supported by a wire to be lost when it eventually breaks.

A model was developed using cinematic of the wire in order to get an estimation of the transfer length depending on assumption on the strain and the displacement of the cut wires on the damaged tendon. A

close formula linking sliding of the wire, assumption on the cinematic form of the strain and transfer length has been derived. This model may prove useful for assessing the reach of damage on industrial tendon.

Another model was created to get a lower bound of the tension loss which translate into an upper bound of the tension. It thus gives another tool for assessing the remaining durability of damaged tendons. The models presented still need more testing to be fully validated. Only part of the tension loss is accounted for in the second model, a way to account for the rotation of the strands in the tension loss expression should be derived.

Acknowledgement

This experiment has been funded by the ASFA.

References

- Abdelatif, A. O., Owen, J. S. & Hussein, M. F. M. (2017), 'Modeling and Parametric Study of the Re-anchorage of Ruptured Tendons in Bonded Posttensioned Concrete', *Journal of Structural Engineering* **143**(12), 04017162.
- Abdullah, A. B. M., Rice, J. A., Hamilton, H. R. & Consolazio, G. R. (2016), 'Experimental and Numerical Evaluation of Unbonded Posttensioning Tendons Subjected to Wire Breaks', *Journal of Bridge Engineering* **21**(10), 04016066.
- Asp, O., Tulonen, J., Kuusisto, L. & Laaksonen, A. (2021), 'Bond and re-anchoring tests of post-tensioned steel tendon in case of strand failure inside cement grouting with voids', *Structural Concrete* **22**(4), 2373–2390.
- Beltrán, J. F., Nuñez, E., Nuñez, F., Silva, I., Bravo, T. & Moffat, R. (2018), 'Static response of asymmetrically damaged metallic strands: Experimental and numerical approach', *Construction and Building Materials* **192**, 538–554.
- Briere, V., Harries, K. A., Kasan, J. & Hager, C. (2013), 'Dilation behavior of seven-wire prestressing strand – The Hoyer effect', *Construction and Building Materials* **40**, 650–658.
- Foti, F. & Martinelli, L. (2019), 'Modeling the axial-torsional response of metallic strands accounting for the deformability of the internal contact surfaces: Derivation of the symmetric stiffness matrix', *International Journal of Solids and Structures* **171**, 30–46.
- Ghoreishi, S. R., Messenger, T., Cartraud, P. & Davies, P. (2007), 'Validity and limitations of linear analytical models for steel wire strands under axial loading, using a 3D FE model', *International Journal of Mechanical Sciences* **49**(11), 1251–1261.
- Godart, B. (2014), *La Pérennité Du Béton Précontraint*, PRESSES DE L'ECOLE NATIONALE DES PONTS ET CHAUSSEES.
- Hyett, A., Bawden, W. & Reichert, R. (1992), 'The effect of rock mass confinement on the bond strength of fully grouted cable bolts', *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* **29**(5), 503–524.

MacDougall, C. & Bartlett, F. M. (2003), 'Tests of Unbonded Seven-Wire Tendon with Broken Outer Wires', *Structural Journal* **100**(5), 581–588.

Watanabe, K., Tadokoro, T. & Tanimura, Y. (2011), 'Evaluation for Flexural-load Capacity of Prestressed Concrete Girders with Broken Tendons', *Quarterly Report of RTRI* **52**, 224–229.