INNOVATION IN TESTING OF LOW RELAXATION STRESSING STRAND

Abstract
The use of low relaxation strand is critical in prestressing concrete structures such as Main Roads’ bridges. The relaxation property of the high tensile stressing strand can be modified by the manufacturing method. Relaxation is the time-dependent change in load when the strand is maintained at constant strain. It has been found that the test methods employed by some strand manufactures can underestimate the relaxation properties of the strand product.

The University of Queensland has three ‘rigid’ relaxation test machines. Since the early 1980s the university has developed testing techniques which provide consistent and accurate test results on the performance and quality of strand product. Main Roads and the University of Queensland have

Introduction
Main Roads commenced testing stressing strand in 1977 when low relaxation seven wire prestressing strand was offered as an alternative product for the 2.7 km long Houghton Highway viaduct in Brisbane. Research and testing work on the quality and performance of strand began at the University of Queensland at that time to verify the strand properties. Since that time Main Roads has maintained a relationship with University of

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Queensland for testing of strand. The University of Queensland undertakes independent relaxation testing of all strand suppliers used by Main Roads as well as other independent tests.

The collaborative involvement of Main Roads and the University of Queensland in relaxation testing of stressing strand allows Main Roads to have confidence in the strand that is supplied for use in the department’s prestressed concrete products. A testing program is vital in providing meaningful input into Australian Standards and the department’s role in quality auditing and quality assurance of strand suppliers. Testing applies to existing and new suppliers to verify the quality and consistency of the strand product. In addition, one of the authors (Ross Pritchard) is working on a Standards Australia Committee BD84 to improve codes with particular reference to better definitions of testing methods for strand. The implemented changes to the current standards AS1310 to AS1313 will be published as a new standard, AS4672.

Low relaxation strand

Stressing strand is a critical structural component in bridge and other pre- or post-tensioned structures. The quality and conformance of stressing strand designed to codes such as AS1311 (9) is fundamental. Strand is a special form of wire ‘rope’ made up of a central wire surrounded by six outer wires helically wrapped around it to form a strand (Figure 1).

Centre strand slightly larger

Figure 1. Cross section trough a stressing strand.

Main Roads uses low relaxation stressing strand in the prestressed concrete products used in the construction of its bridges. If normal relaxation strand is used, this would result in a loss of effective pre-stress in the structure. When normal relaxation strand is stressed to high values (≈ 1470 MPa), the strand will relax slowly, losing as much as 20 to 30% of its prestressing force. The rate of relaxation is initially high, but decreases in a logarithmic fashion over several decades. As bridges have a design life of 100 + years, high relaxation losses would result in a loss of carrying capacity and prestressed concrete decks would sag. This can lead to cracking of the concrete and would seriously affect the durability of the structure.

In this context, relaxation should not be confused with creep. The distinction between these concepts is essential when examining relaxation test methods.

- Relaxation is the time-dependent change in load when the strand is maintained at constant strain.
- Creep is the time-dependent change in strain when the sample is maintained under constant load.

The actual mechanism of relaxation is extremely complex and is the subject of much technical discussion (4, 7, 8). There are certain fundamental statements that can be made.

\[ \varepsilon_{\text{total}} = \varepsilon_{\text{elastic}} + \varepsilon_{\text{inelastic}} = \text{Constant} \]

The elastic behavior can be explained by conventional theory. The inelastic response is more complex. The inelastic or plastic deformation is postulated to be the localized slip or dislocation between adjacent crystals or grain boundaries. In an isothermal environment (constant temperature), it can be demonstrated that the initial rate of crystalline dislocation will be high and will reduce to a constant logarithmic rate.

Normal high tensile prestressing strand is manufactured by cold drawing smooth straight wires and then spinning the wires into a helical strand. To create low relaxation strand, the physical properties of the normal strand are modified by further manufacturing processes. The normal relaxation strand is subjected to an elevated temperature (≈ 400°C), stretched to a strain of approx 1% and finally quenched. The exact details vary between steel mills or production lines. These additional processes led to the introduction of low relaxation strand which is much more stable, losing less than 5% of its stress over the life of a structure.

The consistency and monitoring of process variables are the critical elements in the manufacture of low relaxation strand. If any of the manufacturing process parameters (tension, wire velocity, heating temperature and quenching) are not properly controlled, the strand may not be low
relaxation and could have relaxation losses many times the code requirement.

**Relaxation test standards**

Main Roads Technical Note 16 (10) defines in detail the requirements for a relaxation test. It contains more information than the various Australian Standards. The key features of relaxation testing are to confirm compliance with the requirements of AS 1311 and AS 5100 (1).

AS 1311 defines the relaxation loss at 1000 hours (6 weeks) while AS 5100 Australian Bridge Design Code defines the relaxation loss at 1000 hours and additionally at 10,000 days (30 years). Clearly a 10,000 day test period is impractical. To satisfy the design requirements of both codes it is essential that the 1000 hour test data is sufficiently accurate so that it may be extrapolated to 10,000 days with confidence. This ensures that the long-term relaxation loss values of the design code are satisfied.

Figure 2 shows a typical comparison relaxation test produced by the University of Queensland.

![Figure 2](image1)

**Figure 2. Typical high quality relaxation data.**

**The key features of the plot are:**

- An initial high relaxation loss which becomes linear on Log R–Log t axes after about eight hours.
- In an isothermal test regime with a temperature variation ± 0.5°C in lieu of ± 2°C as permitted by the code, the data plot is linear, with little if any scatter from a straight line.
- Linear regression analysis is used to determine the best-fit line for the data. For a valid test, the correlation coefficient has been found to be always greater than 0.96 and is typically greater than 0.99 where the time ≥ 8 hours.

- The parameters from the linear regression analysis (time ≥ 8 hours) are used to extrapolate to the 10,000-day relaxation loss.

**Relaxation test equipment**

There are a number of types of relaxation machines in current use each incorporating various designs, test methodologies and anchorage systems — all of which can influence test accuracy. There is serious doubt regarding the validity of some suppliers’ test results, and the ability to confidently extrapolate the long-term performance of strand. In 2002, the performance of various relaxation testing machines was investigated (6). The investigation highlighted various shortcomings in the test machines and test practices of various suppliers of strand.

The University of Queensland has three rigid frame relaxation machines with rigid load cells (Figure 3) (3, 6).

![Figure 3](image2)

**Figure 3. Typical view of stressing head in two UQ machines.**

In conjunction with good test procedures, the testing regime of University of Queensland is believed to provide higher quality test data than the majority of others. The key features of the relaxation test equipment and test procedure are:

- The test frames are considered rigid as they have an axial stress of only 22 MPa when loaded to 80% of ultimate tensile strength of the strand. At this load the strand has an axial stress of 1470 MPa. Conversely, a test frame is considered a soft rig if it is designed for a normal full working stress of 150 MPa. From experience, strand tested with rigid frames and
rigid load cells produce linear Log R - Log t plots after an initial period of high relaxation due to crystal dislocation. This initial rapid dislocation lasts typically between 1 to 10 hours depending on the manufacturing methods for the strand.

• One University of Queensland test machine was designed for 12.7 mm strand and the other two machines designed for up to 15.2 mm strand. All machines are designed to accept a 3.3 m long test piece. The longer the test piece, the less anchorage effects can influence the results.

• Swaged anchors are used rather than barrel and wedge anchors to eliminate the effects of anchorage draw-in.

• The ends of the strand are artificially roughened by exposure to salt water for a day to reduce relative slip. The slight etching caused by the rusting increases the friction between the strand and the anchor and between the outer six wires and the centre wire. A dial gauge monitors movement of the center wire relative to the outer wires. Some manufacturers use effective low friction lubricants in the strand drawing process that causes the central wire to slip even when great care is taken with anchorage wedges. The salt water treatment solves this problem.

• The closer tolerance of ± 0.5°C on room temperature ensures a higher correlation coefficient of test results. (Closer to an exact straight line.)

• At the end of a test, the load cell reading at zero load is recorded to ensure there are no residual hysteresis effects in the load cell.

The third rigid frame machine was designed and commissioned in 2006 which incorporated some innovative design features. This machine (Figure 4) was designed by Engineering and Technology Group of Main Roads and constructed by University of Queensland. The machine has a design capacity of 250kN and is suitable for testing both 12.7 mm and 15.2 mm stressing strand. The two previous frame designs each incorporated four synchronised square thread load screws (Figure 3). In both these units, the reduction gearing was purpose designed and incorporating a combination of gearboxes, chains and gears. These purpose designed drive reduction systems are time consuming and expensive to construct.

The new frame (Figure 4 &5) features side frames with an increased cross sectional area to minimise creep during a test. The standard manufacture gearbox has a 2750:1 reduction ratio and drives a single high tensile shaft with an 80 mm diameter buttress thread (12). This single screw thread drives the load crosshead/yoke.

![Figure 4. Plan of new 250kN relaxation frame.](image)
AS 1311 requires that the test load be applied at a uniform rate within a period of 4 to 5 minutes. In this new design, the rate of load application is easily and accurately controlled by utilising a frequency controlled three phase induction motor. The power supply is converted to a variable 0-100 Hz three phase supply. When loading a sample, it is desirable to be able to accurately stop at a specific load. In the older test frames, the high gearbox reduction combined with the inertia of gearbox components make it difficult to stop the test rig quickly and accurately at a specific point. The loading continues momentarily even after the motor is switched off. The new design test frame incorporates an electric motor with a braked armature. When the motor is switched off the armature is locked almost instantly allowing accurate control of the applied test load.

With the older designed frames the strand must firstly be threaded through the end plates and then the anchors swaged. The new machine permits the test piece to be prepared remotely from the test frame in advance and retained with pairs of split collets. Figure 4 shows the split collets and the micro-strain extensometer which measures 1-strain change over a 250mm length of strand.

**Comparison of test methods**

To demonstrate the effects of centre wire slippage, the University of Queensland undertook a series of three tests using different test methods. So that test results were comparable, all strand samples came from the same coil. The ratio of diameters of the centre wire to outer wires was 1.03. Using a larger centre wire helps to reduce slippage. All tests were done on one of the university’s rigid frame machines in conjunction with a rigid load cell.
Figure 6 shows the difference in recorded relaxation losses. After 100 hours, the recorded results indicated a variation of relaxation loss from 1.0% to 3.0% which represents a 300% variation. This test clearly demonstrates the variation in relaxation due to variation in test methods. Strand may be made to pass (method 2) or fail (method 1) by operator made adjustments during the tests.

<table>
<thead>
<tr>
<th>Method</th>
<th>Results</th>
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| 1.     | • Strand as supplied  
          • No slippage on outer wire at anchor  
          • The centre wire slipped  
          • The cross head was held constant |
| 2.     | • Strand as supplied  
          • No slippage on outer wire at anchor  
          • The centre wire slipped  
          • The cross head was moved to keep a constant strain |
| 3.     | • Wire conditioned by rusting of wire in the anchor zone prior to test  
          • No slippage on outer wire at anchor  
          • Centre wire did not slip  
          • The cross head was held constant |

Table 1

Figure 6. Comparison of relaxation results using various test methods

Suggested improvements to AS 1311

The suggested improvements to AS 1311 are based on years of experience in testing strand and monitoring and evaluating test data from many countries.

- AS 1311 needs to clearly define relaxation. This is necessary to help clarify the goals of a relaxation test and ensure manufacturers can acquire equipment to conform to these requirements.
- It has been recommended that the centre to outer wire ratio be increased from 1.02 to 1.035 to ensure that centre wire is properly gripped with normal wedge anchors.
- The 1000-hour test results must pass the current requirements and the data must be of sufficient quality to permit extrapolation to 10,000 days with confidence. The long-term performance of strand is a critical design issue. It is essential to ensure that actual behaviour matches the design assumptions. It is recommended that 5% relaxation loss should be the 10,000 day limit when stressed to 80% UTS. This aligns the design assumptions in the Australian Bridge Design Code with the test limits.
- The tolerance on temperature should be tightened from ± 2°C to ± 1°C. The extrapolation of relaxation losses requires elimination of variables, which induce scatter in the test data.
- It is essential to have sufficient sample length.
to be representative and minimize all end effects. The current code permits a test length of 3 lay lengths (457 mm) for 12.7 mm strand. In a test where any change in length is critical (e.g. compression of load cell), it is essential to have a reasonable length. The minimum test length should be increased to 9 lay lengths (1.4 m), but a 3 m test length is preferred as experience at University of Queensland shows this reduces ‘end effects’ to manageable low levels.

- Previous research (5) highlights the problems associated with various types of test machines. The use of a ‘rigid’ test frame in conjunction with a ‘rigid’ load cell is recommended as it is believed to be the only combination of equipment that can achieve the accuracy required.
- It is recommended that the use of ‘soft’ test frames and/or ‘soft’ load measuring equipment be excluded.
- Any correction of strain or load during a test is not permitted. (If permitted, an operator could correct the result to any desired level.)

Conclusions

Strand is a globally traded commodity and its quality must be confirmed by testing, as it is a critical component in major structures. A testing regime such as the Australian Certification Scheme for Reinforcing Steels is necessary to ensure all manufacturers supplying the Australian market conform to the requirements of Australian Standards and the Australian Bridge Design Code. Testing at the source (at plant or when imported) is more efficient and less costly than testing material on an individual project basis.

The testing procedures in AS 1311 and other associated standards are deficient in detail in a number of areas and are now undergoing review. Relaxation loss requires the accurate measurement of a small change in load at constant strain. Some equipment currently used by suppliers cannot accurately measure relaxation. High accuracy in the 1000 hour test is required as design codes require extrapolation of relaxation loss at 30 years. The University of Queensland is well positioned with three ‘rigid’ relaxation test machines to provide accurate and reliable testing of stressing strand to the appropriate standard. It has the only independent testing rigs in Australia.

References

10. Main Roads Technical Note 16, Method of Acceptance Testing of Low Relaxation Prestressing Strand for Conformance to MRS 11.73