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Critical Assessment of the International Estimates for Relaxation Losses in Prestressing Strands

A. V. KORETSKY and
R. W. PRITCHARD

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Department of Civil Engineering,
University of Queensland,
St Lucia, Q 4067, Australia,
[Tel:(07) 377-3342, Telex:UNIVQLD AA40315]

CRITICAL ASSESSMENT OF THE INTERNATIONAL ESTIMATES FOR RELAXATION LOSSES IN PRESTRESSING STRANDS

by

A.V. Koretsky, BE, ME, MCIA
Senior Lecturer in Civil Engineering

and

R.W. Pritchard, BE, Grad, IE Aust
Civil Engineer, Main Roads Department, Queensland

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Synopsis

This report exposes significant variations in the techniques of measuring relaxation losses in prestressing strands and in the relaxation values recommended by the Australian and International Standards and Design Codes. A specially designed test frame is reported and its capabilities are demonstrated on a series of twenty-four relaxation tests. It is concluded on the basis of the test data obtained that test equipment should be more rigidly specified and standardised and that modifications are required to the current methods of estimating the magnitude of the strand relaxation. Modifications to the Australian Standards are suggested. Areas for particular emphasis are test methods, relaxation losses immediately after stressing, isothermal relationship between the relaxation values at 1000 hours and at ultimate and the time dependent relaxation relationships when steam curing is employed.

CONTENTS

1. INTRODUCTION

Pure stress relaxation is the time dependent loss of prestress which occurs when the strand is maintained at a constant strain. The actual mechanism of relaxation is extremely complex and the subject of much debate (3, 4, 5). It is, however, accepted that certain fundamental statements can be made on the subject, namely -

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{inelastic} = \text{constant} \qquad (1)$$

It is the concept of the inelastic deformation which poses a theoretical problem. The plastic or inelastic deformation is postulated to be the localised slip and diffusion dislocation process between adjacent crystals. Sanchez-Galvez et al (5) have developed a theory of relaxation based on plastic deformation due to thermally activated dislocation motion. This concept provides a basis for the interpretation of the experimental results presented in this paper.

2. REVIEW OF INTERNATIONAL STANDARDS AND DESIGN CODES

During some three years of studying the relaxation behaviour of prestressing strands, (1, 2) the authors have become concerned about the vague manner in which internationally known standards and design codes specify the test equipment. Consequently, there is no really uniform method of evaluating relaxation losses. The following standards and design codes were examined (Refer Table 1, Figs. 4, 5).

- AS 1311 - 1972 "Steel Tendons for Prestressed Concrete" (6)
- ASTM A416 - 1974 "Standard Specification for Uncoated Seven Wire Stress - Relieved Strand for Prestressed Concrete" (7)
- BS 3617-1971 (7) "Standard Specification for Seven Wire Steel Strand for Prestressed Concrete" (8)
- CEB - FIP - 1978 "Model Code for Concrete Structures" (9)
- AASHO - 1975 "Interim Specification for Highway Bridges" (10)
- AS 1481 - 1978 "Prestressed Concrete Code" (11)
- CP 110 : Part 1 - 1972 "The Structural Use of Concrete. Design, Materials and Workmanship" (12)
- DIN 1045 - 1972 "Design and Construction of Prestressed Concrete Structures" (13)
- NAASRA Bridge Design Specification - 1976 (14)

It is apparent from Table 1 that there is a significant variation in the provisions of the International Standards listed. It is not intended in this paper to comment in detail on all of these provisions. Only those points which are directly or indirectly relevant to the reported test series will be discussed. The experience gained in performing these tests provides the basis for the discussion.

The repeatability of the test results is more readily obtained by having a discreet time period between when the test load is obtained and the first reading is taken. This procedure improves repeatability because the initial period of the violent crystal dislocation is neglected. However, as it will be shown later, this procedure is at fault because it ignores significant relaxation losses which take place immediately after stressing of the strand is complete.

Obvious differences exist regarding the representative test length. Extremes of between 14 and 100 strand diameters are specified. Similarly, there is lack of definition in specifying the distance of the gauge length from the anchorage. There is some evidence in the test results presented in this paper to indicate that a longer test length is desirable to minimise the end effects. The test length can be conveniently specified in terms of the basic strand unit known as the lay length. The lay length is defined in ASTM A416 - 1974 (7) as 14-16 strand diameters. Further research is contemplated by the authors into the effect of the test length.

It is generally accepted that whenever a relaxation test is requested, as long as it complies with a current standard, the results are taken as being absolute. To some degree, variations in relaxation values may be due to the properties of the strand steel. However, on the basis of the results obtained by the authors, it will be argued that there are other major contributing reasons -

- Neither the type of the test equipment nor the test length of the tendons are rigidly defined or standardised. In a given situation, different kinds of the test equipment may very well and do provide different results.
- Relaxation losses occurring immediately following completion of stressing cannot be ignored.
- International and local specifications for relaxation tests are so broad that significant differences in relaxation can be obtained depending upon the interpretation of the specification.

3. METHODS OF MEASURING RELAXATION

3.1 Methods and Equipment in Common Use

The accuracy of the test results is related to the testing procedures adopted. The two most commonly used methods of determining the relaxation losses are:

1. Method based on the natural frequency of strand vibration
2. Lever type apparatus.

In the first method, it is necessary to ascertain the natural frequency of the strand to an accuracy of at least ± 0.2 Hz. The time required to determine the natural frequency means that vital initial readings are difficult to record.

The lever type arrangement is widely used. It is relatively complex and expensive. The test length of strands is normally short. The strain is kept constant by adjusting the load. Because of this, the equipment does not quite measure early relaxation losses correctly, as a finite variation in the strain is necessary before the load is adjusted either manually or automatically.

The authors were convinced that first minute readings are crucial for the correct assessment of the relaxation losses. In addition to their inability to do so, the two described methods are not capable of the same resolution and hence do not provide a method of measuring relaxation losses which could be confidently accepted by all International Standards.

These factors combined to encourage the authors to develop a different method of measuring relaxation losses based on the direct and instantaneous recording of the losses through a high precision load cell.

TABLE 1

EXTRACTS FROM THE PROVISIONS OF
THE CURRENT INTERNATIONAL STANDARDS

Factor	AS 1311-1972	ASTM A416-1974	BS 3617(7)	CEB-FIP-1978
Test temperature	20 ± 2°C	20 ± 2°C	20 ± 2°C	20 ± 1°C
Preload prior to test	None		None	0.4 P_i or 0.3 UTS
Test Load Percent UTS	70 or 80	70 or 80	70 or 80	60, 70 and 80
Stressing Time	Less than 5 min.	3-5 min. Load to be applied uniformly	Less than 5 min.	7 min. for super grade tendons stressed to 80% UTS. (1)
First Reading	1 minute after test load is reached	1 minute after test load is reached	1 minute after test load is reached	Test load held 2 minutes. First Reading taken 1 minute after clamping.
Maximum Load	Not to exceed specified test load			
Duration of Test, hrs	1000	1000 (2)	1000	1000
Test Length	100 dia.	60 dia.	1 lay length or 14 dia.	40 dia.
Distance of Gauge Length from Anchorage	-	10 dia.	-	1 lay length
Rotation at end of tendon	Nil	-	-	Prevented
Quality of Testing Frame			-	Accuracy ± .05% of initial load
Anchorage Slip	None	-	None	None
Accuracy of Test Load	(± 2.0% of full load)	1%	-	2%
Lay Length	-	12-16 dia.	-	-

(1) Strain 0.1 ± .025% per min. or stress 20 ± 5 $kg/mm^2/min$.
Load to be applied uniformly.

(2) Shorter if results can be accurately extrapolated.

3.2 Method Designed and Used by Authors

The following requirements were considered in the design of the test method (Fig. 1) -

- Both the test frame and the load cell are sufficiently stiff to ensure that any change in load on the test specimen due to relaxation will have negligible effect on the strain of the strand.
- The test arrangement is adaptable to varying the rate of loading and hence the stressing time.
- The applied load is recorded from the moment the specified test load is reached.
- The recording equipment is capable of indicating the duration of the crystal dislocation period.
- The test frame is long enough to accommodate representative test length of the strand.
- Steam curing of the stressed strand is possible.

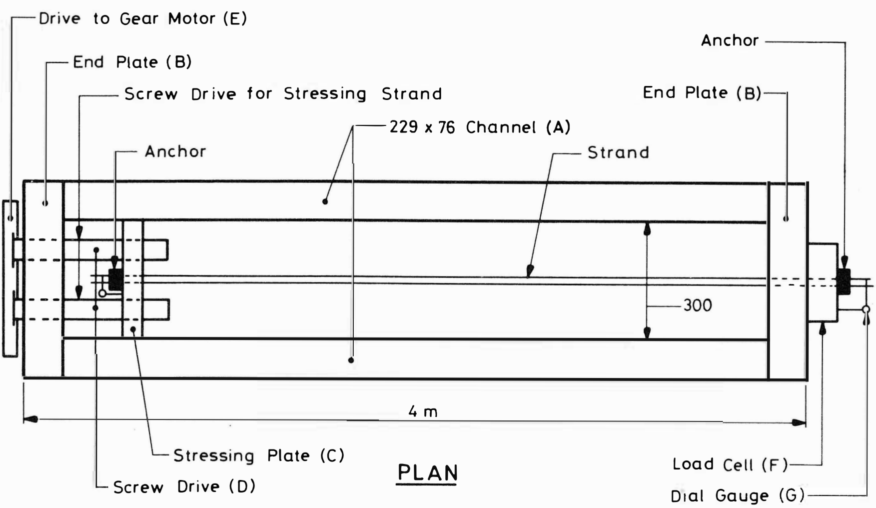

FIGURE 1 : Test frame

The test frame consists of two channels (A) 229 mm x 76 mm x 26 kg (9 in x 3 in x 58 lb). The authors accepted provisions of the Australian Standard AS 1311 - 1972 (6) for the test length of a minimum of 100 strand diameters. To provide for future research into larger diameter prestressing bars, the length of the test frame was set at 4 metres (160 in). End plates (B) are 50 mm (2 in) thick. So is the stressing plate (C). During stressing operations, plate (C) is moved by four screws (D). They are activated through a system of gears driven by motor (E). The rate of loading can be varied by changing gear sprocket combination. High precision "Interface" load cell (F) is attached at the other end of the frame. Strands are anchored between the outsides of the stressing plate (C) and the load cell (F). The initial stressing length is variable (3.3 m (11 ft) in the reported tests). On completion of stressing, plate (C) is firmly held in position by friction in the motor and the gearing mechanism. Swage type anchorages provide a non-slip condition. This verified by dial gauges (G) which measure any slip in the anchors.

The specifications of the load cell are given in Appendix B1. Its compressibility at the rated load of 222 kN (50 kip) is 0.05 mm (0.002 in). The load cell is periodically calibrated to ensure that no hysterisis creep occurs and that the steam curing cycle does not affect the linearity of its response. Data on the compressibility of the test frame is found in Appendix B2.

The test results are recorded on a Phillips Strain Bridge described in Appendix B3. In the tests reported in this paper, the difference between the initial zero and that upon unloading was never more than $\pm$ 0.2 percent of the initial test load. The movement of the Phillips Bridge needle provided indication of the intensity of the crystal dislocation. It is rapid in the early period after stressing, but after some 15 minutes is markedly less.

The system has the capability of recording the readings immediately after stressing of the strand is complete.

4. ISOTHERMAL RELAXATION OF LOW RELAXATION STRANDS

4.1 Test Results

The test results presented in this paper are intended to demonstrate the following major points -

- Significant losses of prestress occur during the first minute after stressing.
- Ignoring of these early readings results in an underestimation of the total relaxation loss. It may also lead to an erroneous relationship between loss at 1000 hours and at ultimate.
- The different test methods result in different time-relaxation relationships.

The reported tests originated in part from some acceptance tests on 12.5 mm diameter seven wire super grade low relaxation strands manufactured by Shinko Wire Co. Ltd., Japan. The tests were undertaken by the Main Roads Department, Queensland in co-operation with the Department of Civil Engineering, University of Queensland, Australia. The study was extended to include fifteen Shinko Strands and four low relaxation and four normal relaxation strands produced by the Australian Wire Industries, Newcastle, New South Wales. When the initial reading is taken one minute after stressing, the manufacturer's specifications for relaxation at 1000 hours at 80 percent of UTS are as follows -

Shinko Wire Company (low relaxation)	3.5 percent
Australian Wire Industries (low relaxation)	3.5 percent
A.W.I. normal relaxation strand	12.0 percent

There is some scatter of the relaxation losses (measured at 1 minute and 1000 hours after loading) given in Table 2. The test values indicate that coil 45 is outside the normal band. High one minute losses R_1 correspond with high 1000 hours values R_{1000}. Both reduce with the decrease in the initial load, but do not appear to depend upon either the stressing time and/or the temperature. It is difficult to view this scatter as being caused by statistical variation between samples or inaccuracies in the recording system. It has been concluded that they are primarily due to two factors -

(a) Extremely rapid and irregular rate of crystal dislocation. The adopted recording system made it obvious through fluctuations of the Phillips Bridge needle. This fluctuation was restricted to the early stages of loading only.

(b) Difficulties in maintaining a precise stressing time and the rate of loading. For this reason, a motor with an accurate variable speed control should give more consistent results.

These factors resulted in some difficulties in correlating the initial load, stressing time and zero relaxation readings.

TABLE 2. SUMMARY OF ISOTHERMAL RELAXATION TESTS ON 12.5 mm STRAND

Test	Strand *	Coil	Stress Time sec	Load Percent UTS (1311)	Test Time t Hrs	Loss Equation Percent	R_1 Percent	R_{1000} Percent	$R_{1000}-R_1$ Percent	AS 1311 R_{1000} Percent	R_1/R_{1000}	R_{ult} Percent	R_{ult}/R_{1000}
A_1	LRS	45	180	80	1000	R = 2.21 + 0.32 Log (t)	0.80	3.16	2.36	3.5	0.25	4.13	1.31
A_2	LRS	45	200	80	200	R = 1.85 + 0.35 Log (t)	0.49	2.90	2.41	3.5	0.15	3.95	1.36
C_1	LRS	184	200	80	170	R = 3.07 + 0.61 Log (t)	1.00	4.90	3.90	3.5	0.20	6.70	1.37
C_2	LRS	184	185	80	142	R = 2.50 + 0.62 Log (t)	0.59	4.35	3.76	3.5	0.14	6.21	1.43
D	LRS	143	180	80	560	R = 3.05 + 0.42 Log (t)	0.96	4.32	3.36	3.5	0.22	5.58	1.29
E_1	LRS	51	90	80	1000	R = 2.70 + 0.70 Log (t)	1.12	4.80	3.68	3.5	0.23	6.90	1.44
F_1	LRS	97	85	80	1000	R = 1.90 + 0.57 Log (t)	0.48	3.60	3.12	3.5	0.13	5.31	1.48
F_2	LRS	97	75	75	1000	R = 1.68 + 0.62 Log (t)	0.36	3.55	3.19	+	0.10	5.41	1.52
E_2	LRS	51	90	75	1000	R = 2.50 + 0.28 Log (t)	0.73	3.35	2.63	+	0.22	4.19	1.25
G	LRS	*	73	70	1000	R = 0.8 + 0.45 Log (t)	**	2.14	2.14	2.5	-	3.49	1.63
H_1	LRS	97	155	70	961	R = 1.59 + 0.45 Log (t)	0.64	2.94	2.30	2.5	0.22	4.29	1.46
H_2	LRS	97	135	50	48	R = 1.41	0.42	1.41	0.99	-	0.30	1.41	1.00
I_1	LRA	1	200	80	343	R = 2.40 + 0.55 Log (t)	1.08	4.05	2.97	3.5	0.27	5.70	1.41
I_2	LRA	1	85	70	1000	R = 0.80 + 0.45 Log (t)	0.30	2.15	1.85	2.5	0.14	3.50	1.63
J_1	LRA	2	190	80	144	R = 1.85 + 0.55 Log (t)	0.75	3.50	2.75	3.5	0.21	5.15	1.47
J_2	LRA	2	150	70	2069	R = 1.15 + 0.25 Log (t)	0.51	1.90	1.39	2.5	0.27	2.65	1.39
B_1	NRA	1988	210	80	2000	Log (R) = 0.44 + 0.16 Log (t)	0.58	8.30	7.72	12.0	0.07	25.00	3.01
K_1	NRA	2001	165	80	1000	Log (R) = 0.41 + 0.156 Log (t)	0.82	7.60	6.78	12.0	0.11	22.18	2.92
B_2	NRA	1988	140	70	750	Log (R) = 0.18 Log (t)	0.55	3.55	3.00	7.0	0.15	10.00	2.82
K_2	NRA	2001	110	50	48	R = 1.07	0.50	1.07	0.57	-	0.47	1.07	1.00

Relaxation losses R_1 during the first minute after stressing amount to 10 to 27 percent of R_{1000}. These readings are consistently larger for higher values of the test load. The authors suggest that it is due to a more rapid and irregular crystal dislocation at higher test loads. Higher R_1 values consistently result in higher R_{1000} values which may exceed manufacturer's specifications.

Neither R_1 nor R_{1000} values appear to depend upon the stressing times used in the tests. The authors are aware of some research work done on the effects of the stressing time on the relaxation loss values. Bridon Wire (15) recorded a 15 percent reduction in R_{1000} value when stressing time was increased from three to ten minutes. Although ten minutes is close to the maximum stressing time in CEB-FIP (1978) (Table 1), it is doubtful that such a long duration of stressing will model the common field conditions.

In the reported tests, stressing times between 90 and 200 seconds were examined. The former is specified in the Japanese Standards. Arrangements were made with Shinko Wire Company to duplicate some tests performed by the authors. Therefore, for comparability purposes, it was necessary to maintain the same stressing times. Three minutes can be regarded as an intermediate range which falls within the standard limits. Some further research into the effects of five minutes stressing may be desirable.

The authors would like to point out that with the gear-sprocket system used, some difficulties were experienced in obtaining ideally accurate time correlation between the test load, stressing time and zero relaxation readings. A motor with an accurate variable speed control for moving screws (D) in Figure 1 should be an improvement.

The intensity of crystal dislocation declines with time. If the time base is transformed so that relaxation is defined as commencing 15 minutes after completion of stressing, agreement between the test readings becomes almost perfect (Figure 2). It should be emphasised that the intention here is to illustrate the validity of the assumptions, not to provide time-relaxation relationship suitable for extrapolation. Early relaxation losses cannot be ignored.

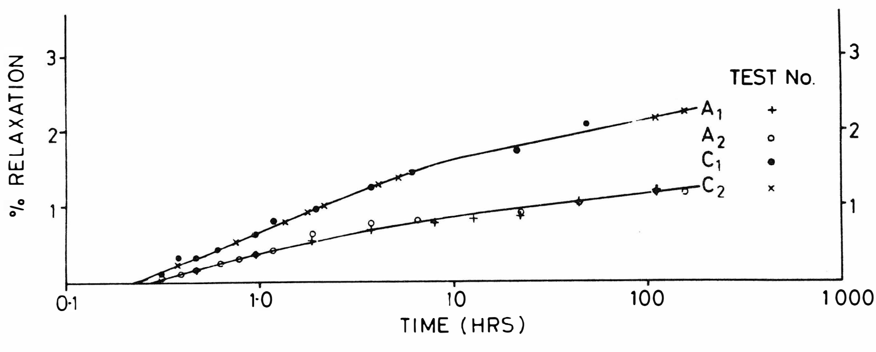

FIGURE 2 : Relaxation on a transformed time base

Another important conclusion to be drawn from the reported tests is the difference in measured relaxation between low and normal relaxation strands. The former exhibit linear behaviour in log time, $R = A + B * \log(t)$, when $t > 10$ hours, whilst the latter exhibit a linear log - log relationship, $\log(R) = C + D * \log(t)$, with $t > 5$ hours.

It is apparent that the fundamental relaxation characteristics of the two types of strand are different. This confirms observations previously reported by Mihailov (3). It is suggested that these conclusions should be noted when code clauses for extrapolation of 1000 hours test to the "life of the structure" are drafted. Tables 4 and 5 demonstrate that this is not the case.

In order to do this accurately, the following conditions should be satisfied -

(a) Time-relaxation relationship should plot as a straight line.

(b) Scatter of the test readings should be sufficiently small so that the error in extrapolating from 10^3 hours to 10^6 hours, i.e. ten decades forward, does not exceed $\pm$ 0.25 percent.

These assumptions have evolved in conjunction with the reported testing program.

4.2 Use of Different Methods and Equipment

Arrangements were made with Shinko Wire Company Ltd. and Australian Wire Industries to test strands from the same coils. Shinko Wire Company agreed to use both the load cell and the lever type methods, Australian Wire Industries used only the lever method. Specifications of the load cell used by Shinko Wire Company are summarised in Appendix B4. It is not as accurate as the "Interface" load cell used by the authors (Appendix B1).

The lever mechanisms could record strain changes of $\pm 2.5 * 10^{-6}$.

TABLE 3

RELAXATION LOSSES Vs TEST METHOD USED

	Test Length m	ft	Stressing Time Sec	R_{1000} Percent
Authors	3.3	11	85	3.12
Shinko Co. - Load Cell	3.1	10	90	3.15
- Lever	0.5	1.6	90	2.70
AWI - Lever	0.5	1.6	135	2.90

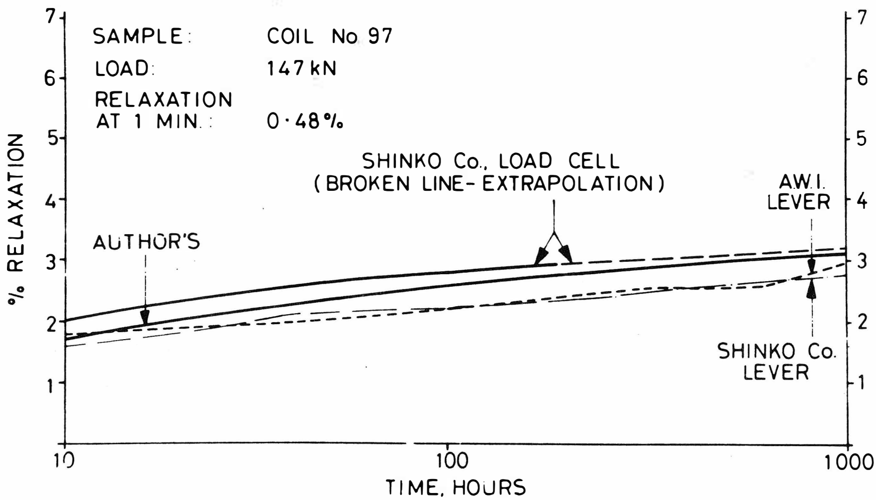

FIGURE 3 : Relaxation losses versus test method used

The test results for strands from coil No. 97 (Test F_1, Table 2) are shown in Table 3 and Figure 3. The standard procedure used by Shinko and AWI was to take the first reading at one minute after stressing. To make the comparison valid, first minute relaxation loss is subtracted from the result by authors, $R_{1000} - R_1 = 3.60 - 0.48 = 3.12$ percent. It is obvious that this procedure, although complying with the standards, ignores significant losses occurring during the first minute and does not record the true value of the relaxation loss.

Consequently, the result by the authors is lower, but much more linear than the one obtained by Shinko Wire Company using load cell system. The values obtained with the lever type testing machine are less regular and consistently lower than the ones resulting from the load cell method.

In fact, the difference is quite significant. The authors' test indicates the true value of R_{1000} of 3.60 percent, whereas the lever method resulted in R_{1000} of 2.85 percent. Apart from ignoring the R_1 reading, low value obtained in the lever test could be due, at least in part, to a very short test length of the strand.

The results discussed in this section indicate overall reliability of the procedures adopted by the authors. Furthermore, it confirms their opinion that significant differences may result depending which method of testing is used.

4.3 Comparison of Test Results with Design Codes

The experimental evidence summarised in Table 2 will be compared with the Design Codes previously mentioned: AASHO - 1975 (10), CEB-FIP - 1978 (9), CP 110 : Part 1 - 1072 (12), DIN 1045 - 1972 (13) and NAASRA - 1976 (14). The relaxation values in the British Standard CP 110 include effects of the creep and shrinkage of concrete, something that is outside the research reported in this paper. The losses due to creep and shrinkage of concrete should increase the overall loss of prestress available in the strands. Therefore, for comparison purposes, the relaxation values in CP 110 are not quite relevant and should be regarded as a guide only. The Design Code values for low relaxation strands are summarised in Figure 4. Their comparison with the upper bound values from the test results by the authors is presented in Table 4.

Test H_2 (Table 2) was specifically designed to ascertain if any relaxation losses occur when low relaxation strand is stressed to 50 percent of its UTS. Table 2 indicates that the first minute relaxation is not insignificant at 0.42 percent. The loss increases to 1.41 percent within the first two hours. No further relaxation occurs thereafter. Thus, the form of the loss equation R = 1.41.

TABLE 4

RELAXATION LOSSES FROM TEST RESULTS Vs DESIGN CODES

	LOAD 0.8 UTS		LOAD 0.7 UTS	
	R_{1000} Percent	R_{ult} Percent	R_{1000} Percent	R_{ult} Percent
Authors - LRS	5.0	7.0	2.15	3.50
Authors - LRA	4.0	6.0	2.15	3.50
AASHO	2.25	4.30	1.50	3.00
AS 1481, NAASRA	3.50	7.00	2.50	5.00
CEB-FIP	2.90	10.00	1.75	6.00
CP 110	3.50	3.50	2.50	2.50
DIN 1045	-*	-*	2.00	7.00

* Not given

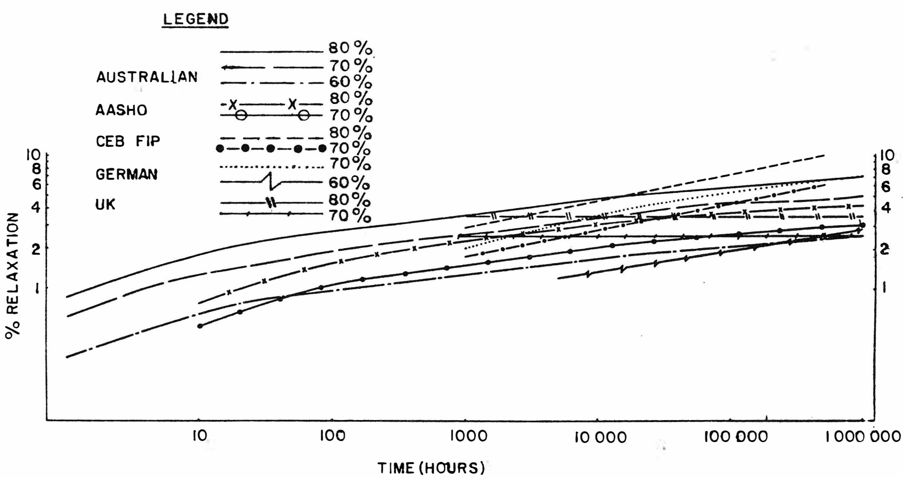

FIGURE 4: Relaxation losses versus time-low relaxation strand

Table 4 clearly indicates significant variation in the values of relaxation losses recommended by the International Design Codes at all levels of prestress. These values ignore relaxation losses during the first one or two minutes after stressing. On the other hand, values in Table 4 quoted by the authors do take these initial losses into account. In general, they lie between the rather wide limits found in the various codes. The only exception is the 1000 hours relaxation loss R_{1000} at 0.8 UTS which is consistently lower in the Design Codes.

Another important fact that emerges from this comparison is that the relationship between the values of R_{1000} and R_{ult} resulting from authors' tests is clearly at variance with the ones accepted by the various codes. From the authors' tests $R_{ult} = CR_{1000}$, where C = 1.4 for low relaxation strands.

5. ISOTHERMAL RELAXATION OF NORMAL RELAXATION STRANDS

5.1 Test Results

Limited number of tests performed provided results clearly close to the values in CEB-FIP - 1978 (9). However, the relationship between R_{1000} and R_{ult} values is not quite the same. It follows the log-log time line discussed in Section 4.1. It should be noted that the authors' values include first minute relaxation losses, whereas those in CEB-FIP do not.

It is intended to continue tests on normal relaxation strands produced by other manufacturers with a view of verifying the validity of log-log time-relaxation relationship.

5.2 Comparison of Test Results with Design Codes

The Design Code values for normal relaxation strands are summarised in Figure 5. They are compared with the upper bound test values in Table 5.

Test K_2 (Table 2) was performed to examine the behaviour of the normal relaxation strands when stressed to 50 percent of their test UTS. As in the case of low relaxation strands (Section 4.3), very little relaxation takes place after noticeable first minute loss.

Relationship between the values of R_{1000} and R_{ult} resulting from the authors' tests is different from the ones accepted by various codes. The Authors' tests indicate -

$$R_{ult} = CR_{1000}, \text{ where}$$

$$C = 3.0 \text{ for normal relaxation strands.}$$

The nearest approximation to this magnitude of coefficient C is found in the values quoted by CEB-FIP - 1978 (9).

6. EFFECT OF LOW PRESSURE STEAMING ON BARE LOW RELAXATION STRANDS

6.1 Test Results

Except in Australian Design Codes AS 1481 - 1978 (6) and NAASRA - 1976 (14), very little information is available on how to predict relaxation losses in strands subjected to steam curing cycle. The test series reported in Table 6 was designed to ascertain the trends which occur in relaxation losses subsequent to steaming of the bare strands.

TABLE 5

RELAXATION LOSSES FROM TEST RESULTS Vs DESIGN CODES

Source	Load 0.8 UTS		Load 0.7 UTS	
	R_{1000} Percent	R_{ult} Percent	R_{1000} Percent	R_{ult} Percent
Authors - NRA	8.30	24.00	3.6	10.00
AASHO	*	*	9.00	17.00
AS 1481, NAASRA	12.00	24.00	7.00	14.00
CEB-FIP	7.20	25.00	3.50	13.00
CP 110	12.00	12.00	8.00	8.00
DIN 1045	*	*	7.50	17.00

* Not Given

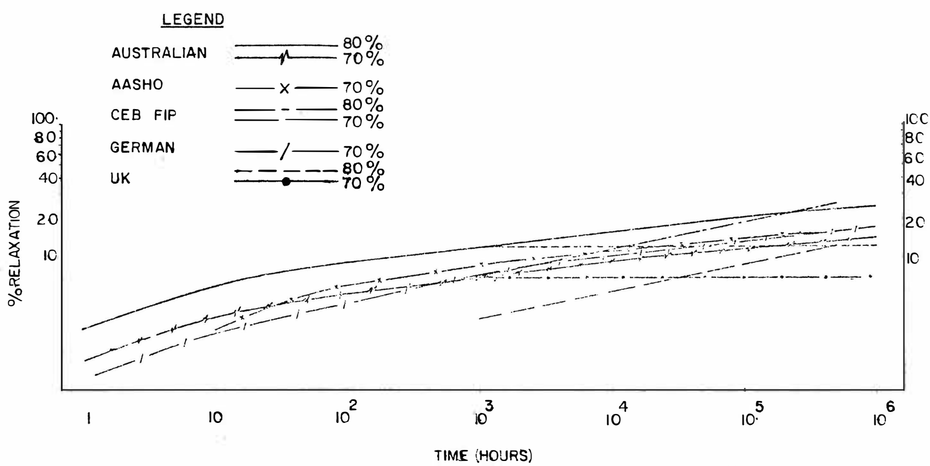

FIGURE 5: Relaxation losses versus time-normal relaxation strands

TABLE 6

SUMMARY OF TESTS ON STRANDS SUBJECTED TO STEAMING CYCLE

Test	Strand	Coil	Stress Time Sec	Load Percent UTS (1311)	Test Time Hrs	t_i Hrs	t_s At 80°C Hrs	Maximum R_{st} Percent	R_{sult} Percent
K_1	LRS	97	90	80	1000	18.5	5.5	9.82	8.15
K_2	LRS	97	80	80	200	15.0	4.0	13.00	10.60
L_1	LRS	51	85	80	300	64.0	6.0	11.15	9.90
L_2	LRS	51	90	80	720	16.0	6.0	9.00	7.20

The variation in temperature experienced in any one test will not significantly affect the relaxation losses as long as the testing frame and the strand remain at the same temperature and have the same thermal characteristics. The stressing frame and the strand are both made of steel and would be expected to have similar coefficients of thermal expansion. Even if there is a small temperature differential between the two, say $\pm$ 0.5°C, it will result in an error of only $\pm$ 0.7 percent in the relaxation value recorded.

6.2 Behavioural Patterns

Despite variation in the time t_i after stressing when steam was applied and in the duration of steaming t_s shown in Table 6, two important behavioural patterns emerge (Figure 6) -

- No further relaxation occurs on completion of the steaming cycle.
- Steaming causes ultimate relaxation loss R_{ult} to increase by some 50 percent over losses in non-steamed strands.

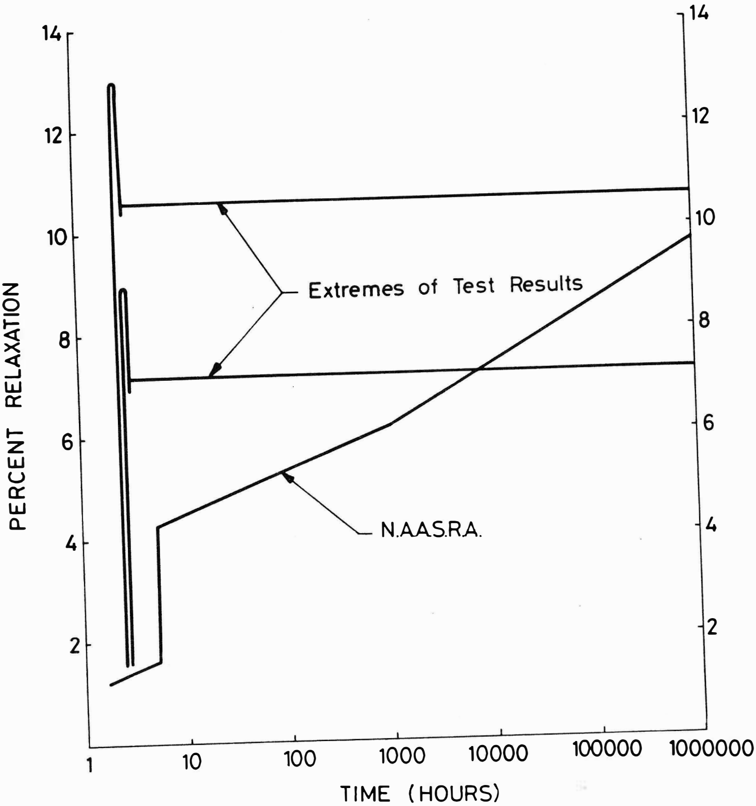

FIGURE 6 : Losses due to steaming LRS

The test results are certainly at variance with the design curve based on the Australian Codes AS 1481 - 1978 and NAASRA - 1976, but agree in principle with the results by other manufacturers for similar strands in FIP Report on Prestressing Steel No. 3 (16). As far as current Australian Codes are concerned, equations predicting losses of prestress due to steam curing should be reviewed (Figure 6).

It is concluded that during the steam curing cycle, the imposed thermal excitation results in all crystal dislocations taking place in a shortened period of time. Crystalline structure is such that no distinct relationship exists between the time of steam application and the duration of steam curing, on the one hand, and the final relaxation loss after steaming R_{sult}, on the other. However, low and high values of R_{sult} form a relatively narrow band between 7.20 and 10.6 percent (Figure 6).

7. CONCLUSIONS AND RECOMMENDATIONS

There are obvious differences between the actual behaviour of the strands and the relevant provisions in the Australian and International Standards and Design Codes. The major contributing factors are -

- Neither the test equipment nor the length of strands are rigidly defined or standardised
- Significant early relaxation losses during the first minute or so after stressing are completely ignored.

This in turn leads to an erroneous relationship between the 1000 hours relaxation loss R_{1000} and the ultimate relaxation loss R_{ult}.

On the basis of the reported findings, the authors suggest several modifications to the Australian Standards AS 1311 and AS 1481 and to the NAASRA Design specification. Suggested modifications are listed in Sections 7.1 - 7.4.

It is also intended to send copies of this Report to the major International Organisations responsible for issuing relevant standards and design codes.

7.1 Test Procedure

It is the belief of the authors that Australian Standard AS 1311 does not adequately define the procedure for conducting a relaxation test. It is suggested that consideration be given to the inclusion of the following points -

(a) The equipment should be capable of measuring the change in the applied load immediately after loading is completed. The first reading should be taken at this point of time, not one minute after completion of stressing.

(b) To enable accurate extrapolation, the test equipment should have a degree of precision not less than 0.02 percent.

7.2 Isothermal Relaxation at 1000 Hours

On the basis of test results obtained, it is recommended that current limits are reviewed as follows -

Grade of Strand	Load 70% UTS	Load 80% UTS
Normal	*	8
Low Relaxation	2.5	5

* Insufficient data at this stage.

Recommended limits are closer to the performance of the commercially available strands.

7.3 Isothermal Ultimate Relaxation

Time-relaxation relationship is erroneously defined in the current provisions of the Australian Codes. Test results clearly show a uniform relaxation loss with respect to the log time. There is no increase in this rate after 1000 hours. It is suggested, therefore, that the estimate of the ultimate losses is based on the log time relationship, thus

$$R_{ult} = CR_{1000}, \text{ where}$$

$C = 1.4$ for low relaxation strands

$C = 3$ for normal relaxation strands

7.4 Low Pressure Steam Curing

Results obtained in the test program are at variance with the Code provisions. It is suggested that the latter are amended to incorporate the following -

(a) no further relaxation occurs on completion of the steaming cycle

(b) ultimate loss in steamed strands R_{sult} is some 50 percent higher than in non-steamed strands.

8. ACKNOWLEDGEMENT

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APPENDIX A - NOMENCLATURE

Symbol	Meaning
AWI	Australian Wire Industries, Newcastle, N.S.W., Australia
d	Strand diameter
LRA	AWI super grade low relaxation strand
LRS	Shinko Wire Co. Ltd., Tokyo, Japan, super grade low relaxation strand
NRA	AWI normal relaxation strand of regular grade
R_1	Relaxation loss at one minute
R_{1000}	Relaxation loss at 1000 hours
R_{st}	Relaxation loss in bare strands at the time steam is cut off
R_{sult}	Final relaxation loss after low pressure steaming
R_t	Relaxation loss at time t in non-steamed strands
R_{ult}	Relaxation loss at 10^6 hours in non-steamed strands
t	Time t
t_i	Time after stressing when steam is applied
t_s	Duration of low pressure steam curing
UTS	Specified minimum ultimate tensile strength of strands
ε	Relaxation strain

APPENDIX B - TEST FRAME AND INSTRUMENTATION

B1. "Interface" Load Cell. Specifications of the 222 kN (50 kip) capacity "Interface" load cell are -

Zero balance	0.2% of the rated load (RL)
Output	4.042 mV/V
Thermal zero shift	0.0001% (RL)/^{o}C
Compensated temperature range	-9^{o}C → 80^{o}C (15^{o}F → 175^{o}F)
Non-linearity hysterisis and repeatability	± 0.014% of full scale
Compressibility at RL	0.05 mm (0.002 in)
Compressibility at 147 kN (33 kip)	0.03 mm (0.001 in)

B2. Frame Compressibility. At the 0.8 UTS load of 147 kN (33 kip), the stress in the frame amounts to 22.14 N/mm^2 (0.46 ksi). Assuming five percent relaxation loss, the consequent change in the frame length would amount to 5 * 10^{-4} percent.

B3. Phillips Strain Bridge. The Bridge was used to monitor the force in the load cell. Bridge specifications are -

Voltage supply	10 ± 0.01 DCV
Accuracy	± 0.02%

B4. Load Cell used by Shinko Wire Co. Specifications of the 196 kN (44 kip) capacity load cell are -

Output	2.0 mV/V
Repeatability	± 0.1% of full scale
Non-linearity hysterisis	± 0.4% of full scale

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