Low-Relaxation Strand—Practical Applications in Precast Prestressed Concrete

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The development of seven-wire stress-relieved strand was one of the most important factors in the growth of prestressed concrete as a standard material of construction. Just as the precast, prestressed concrete industry has matured into using wider, deeper, heavier and more economical sections, so the seven-wire strand has also changed to meet this demand.

From a basic standard of 250 ksi (1720 MPa) in ⅜, 7/16, and ½ in. (10, 11, and 13 mm) diameter 25 years ago, strand has developed to the point where 0.5 and 0.600 in. (13 and 15 mm), 270 ksi (1860 MPa) is the standard used today. In addition, low-relaxation strand is now making its presence felt over the once commonly used stress-relieved material because it has significantly less loss of initial tension. This can result in improved and more predictable service performance, and in many cases will allow a higher load carrying capability.

In 1957, the American Society for Testing and Materials issued the first "Standard Specifications for Uncoated Seven-Wire Stress-Relieved Strand for Prestressed Concrete" (ASTM A416). Today, the 1980 ASTM A416 standard[1] includes low-relaxation strand. This specification requires that the low-relaxation strand differ from ordinary stress-relieved strand in only two respects: first, it must meet certain relaxation loss requirements, as measured by ASTM E328[2] (note that ordinary stress-relieved strand has no such requirement); and second, the minimum yield strength, as measured by the 1 percent extension under load method, must be not less than 90 percent of the specified minimum breaking strength, as opposed to 85 percent for normal stress-relieved strand. All other requirements are the same.

This paper presents the results of an analytical study of the use of low-relaxation strand in the most commonly used precast prestressed products. Most of the data were obtained from the computer program LODTAB, which was the program used to generate the design load tables in the PCI Design Handbook[3] and those used by several precast concrete producers in their own catalogs. This program permits prestress losses to be input as a fixed percentage of initial tension, or calculated by the method recommended by Zia et al.[4] In addition to comparing load capability and service performance, some concerns expressed by potential users and specifiers will be addressed.

It should be noted that this study only compares the maximum capability of the members, based on the above method of loss calculation. The strand savings shown are for those conditions. Overall strand savings to the precaster or on a project will be a function of the product mix and the number of members designed to approach maximum capacity.

Synopsis

This paper evaluates the advantages of designing prestressed concrete members with low-relaxation strand. It also investigates the feasibility of using higher initial strand tension (75 percent of nominal breaking strength), and answers some of the questions regarding the most efficient use of low-relaxation strand and what effects mixing it with stress-relieved strand might have.

The main conclusions of this paper show that low-relaxation strand can result in strand savings, especially in the longer, heavier structural members. Low-relaxation strand can also provide improvements in deflection and cracking control. It is also shown that low-relaxation strand can be mixed with stress-relieved strand in a design based on stress-relieved strand properties without harmful effects.

Loss of Prestress

Until the mid-1960's, the most common design practice was to assume a lump sum value of 35,000 psi (241 MPa) for prestress loss for pretensioned members. This value is based on the 1958 report of ACI-ASCE Committee 323,[5] which served as the basis for design for prestressed concrete until the first ACI Code provisions in 1963. This value is still mentioned in the ACI Code Commentary as giving "satisfactory results for many applications." However, the performance of some long-span, heavily prestressed members seemed to indicate that the lump sum value underestimated the total loss.

In 1971, the PCI Design Handbook Committee selected a uniform value of 22 percent of initial (jacking) tension for use in the load tables in the first edition of the Handbook, which was also retained in the second edition. For 270-ksi (1860 MPa) strand stressed to 70 percent of ultimate, that value is 41,580 psi (287 MPa).

The ACI Building Code[6] specifies the factors which contribute to prestress loss for pretensioned members. They include the long-term effects of creep, shrinkage and tendon relaxation, and the immediate (upon release) effect of elastic shortening. Considerable research has been done on the subject, resulting in a variety of design recommendations. Reference 4 includes a bibliography of these research recommendations.

In 1975, the PCI Committee on Prestress Losses presented a report which included a general and a simplified method for computing losses.[7] As with many of the other methods mentioned above for many members, this method seemed to predict values that were higher than experience could justify.

In 1979, a working group of ACI-ASCE Committee 423, Prestressed Concrete, developed a calculation method which was largely based on earlier work, tempered by the experience of members of the group.[4] This calculation method is the one used in this study. One of the primary differences between this method and others is that upper limits are included. However, no lower limits are specified, and subsequent use of these equations sometimes yields values which are suspiciously low. Therefore, the program LODTAB also places a lower limit of 35,000 psi (241 MPa) for stress-relieved strand, and 30,000 psi (207 MPa) for low-relaxation strand.

It should be noted that prestress loss has virtually no effect on the ultimate strength of the member, at the level of prestress normally used in pretensioned products.

Initial (Jacking) Tendon Stress

It has been the practice in the precast, prestressed concrete industry to apply an initial tension of 70 percent of the nominal strength of the strand when using ordinary stress-relieved strand. Stress relaxation losses in ordinary strand have been shown to be proportionally higher when an initial stress higher than 70 percent is used, to the point that the gain in actual prestressing of the concrete is minimal.

With low-relaxation strand, the relaxation loss remains more or less proportional up to an initial stress of 75 percent of ultimate, so there is often a definite advantage of higher tensioning forces. Furthermore, all manufacturers of low-relaxation strand approve the use of the higher stressing force at 75 percent of nominal strength.

Comparison of Load-Carrying Capability

The flexural capacity of prestressed concrete members is limited by two criteria: (1) Stresses at service load and (2) Ultimate design strength. In addition, the ACI Building Code and the AASHTO specifications limit the concrete stress at the time of transfer of prestress.

When the ultimate design strength of members is calculated using compatibility of strains, there is some indication that low-relaxation strand may provide somewhat greater capacity than ordinary stress-relieved strand because the minimum yield strength is higher. However, typical stress-strain curves shown in the PCI Design Handbook make no distinction between the two materials. The curves in the Handbook were checked against about 25 actual curves of both types from different manufacturers, and little difference was found. The computer program LODTAB is based on these typical stress-strain curves, so no difference in ultimate design strength will be indicated.

The actual area of both stress-relieved and low-relaxation strand may be somewhat different from the area shown in ASTM A416. However, the standard specifically exempts cross-sectional area from any tolerance limitation. The minimum breaking strength is specified as a specific force, which is the product of the strand grade [250 or 270 ksi (1720 or 1860 MPa)] times the nominal or specified strand area.

For example, while the actual cross-sectional area of ½ in. (13 mm) 270 ksi (1860 MPa) strand is, say, 0.158 sq in. (102 mm^2), the minimum breaking strength is 41.3 kips (270 x 0.153) (285 MPa). Therefore, the *nominal* area of the strand [e.g., 0.153 sq in. (99 mm^2) for ½ in. (13 mm) diameter] should always be used for design and for the initial force to be applied to the strand.

The ACI Building Code permits a maximum tensile stress under service load of $12\sqrt{f'_c}$ ($1.0\sqrt{f'_c}$) provided certain deflection criteria are met. It is common practice in the prestressed concrete industry to design to this maximum in stemmed deck members such as double tees and single tees. For flat deck members, such as hollow-core slabs, and for beams, the most common practice is to limit the tensile stress to $6\sqrt{f'_c}$ ($0.5\sqrt{f'_c}$). This is the procedure followed in the PCI Design Handbook and in the analyses that follow.

In addition to flexural criteria, it is common practice to also limit loading in hollow-core and solid-slab deck members to the shear strength of the concrete, since it is very difficult to reinforce for shear. Since the amount of prestress in a slab influences the shear strength, slabs which use low-relaxation strand may have a slightly higher capacity at heavily loaded short spans. This effect is minor, however.

A variety of precast, prestressed concrete sections commonly used in building and bridge construction were investigated in this study, as listed below. The building sections and strand patterns were taken from the second edition of the PCI Design Handbook.[1] The number in parentheses refers to the page from that publication on which the section appears. (Note: for the hollow-core section investigated, actual strand numbers and sizes were used rather than the "strand designation code" used in the Handbook.)

(1) 8 in. Hollow-core, normal weight—4HC8 (p. 2-27)
Strand patterns: 7⅜, 4½, 5½, 6½, 7½ in.
Straight strands at 1½ in. from bottom

(2) 12-in. Hollow-core, normal weight—4HC12 (p. 2-31)
Strand patterns: 6½, 7½, 8½ in.
Straight strands at 1½ in. from bottom

(3) 12-in. Hollow-core, normal weight, with 2 in. normal weight composite topping—4HC12 + 2 (p. 2-31)
Strand patterns: 6½, 7½, 8½ in.
Straight strands at 1½ in. from bottom

(4) 24-in. Double tee, normal weight—8DT24 (p. 2-16)
Strand patterns: 68-S, 108-D1, 128-D1, 148-D1

(5) 24-in. Double tee, normal weight, with 2 in. normal weight composite topping—8DT24 + 2 (p. 2-16)
Strand patterns: 68S-108-D1, 128-D1

(6) 24-in. Double tee, lightweight concrete—8LDT24 (p. 2-17)
Strand patterns: 68-S, 108-D1, 128-D1, 148-Dl

(7) 32-in. Double tee, normal weight—8DT32 (p. 2-18)
Strand patterns: 168-D1, 188-D1, 208-D1, 228-D1

(8) 36-in. Single tee, normal weight—8ST36 (p. 2-22)
Strand patterns: 168-D1, 188-DA, 208-D1, 228-D1

(9) 36-in. Single tee, lightweight—8LST36 (p. 2-23)
Strand patterns: 168-D1, 188-D1, 208-D1, 228-D1

(10) Inverted tee beam 24IT36 (p. 2-52)
Strand patterns: 12, 14, 16, 18, and 20 straight strands

(11) Type IV AASHTO girders with 24, 30, 33, 36, and 42 strands.

For each of the sections and strand patterns, three separate load tables were generated: one with ordinary 270 ksi (1860 MPa) stress-relieved strand,

Note: 1 in. = 25.4 mm.

initially tensioned to 0.70 of the guaranteed ultimate strand strength (f_{pu}); one with 270 ksi (1860 MPa) low-relaxation strand initially tensioned to 0.70 f_{pu}; and one with 270 ksi (1860 MPa) low-relaxation strand initially tensioned to 0.75 f_{pu}.

This variation enabled not only a comparison of the load carrying capacity of members made with each type of strand, but also how much of the difference in capability is attributable to the relaxation characteristics, and how much is caused by the difference in initial tension.

The significant results of these computer outputs are summarized in Tables 1 through 5 and shown graphically in Figs. 1 through 5. Not all strand patterns investigated are shown—only those which indicate a difference in load capacity, which are the maximum number of strands recommended for each section. In general, designs which call for fewer strands than those shown will usually be controlled by the ultimate strength with no increase in capacity under the assumptions used. A few generalizations can be made as follows:

1. Hollow-core slabs—The use of low-relaxation strand shows an increase in load capacity of generally less than 10 percent, all of which is due to less strand relaxation. Increasing initial tension does not increase capacity. For many—probably most—applications, the maximum span is limited by dead load deflection (loss of camber).

2. 24-in. Double tees—This is the most commonly used stemmed section, and significant strand savings can be realized in many applications by using low-relaxation strand. For example, at a span of 70 ft (21.3 m), with a superimposed load of 40 psf (1.9 kPa) [10 psf (0.5 kPa) dead load, 30 psf (1.4 kPa) live load], 14 ordinary stress-relieved strand would be required, whereas 12 low-relaxation strands would be adequate, even without increasing the initial tension. Also with the fewer strand, a lower release strength is required [less than 3500 psi (24 MPa) vs. 4100 psi (28.3 MPa)]. Similar savings are shown in double tees with topping or thickened flanges in the span ranges most commonly used in parking structures.

3. Long span roof members—For long span members typified by the 32 in. (813 mm) double tee and 36 in. (914 mm) single tees investigated, the increased capacity becomes even more significant, as more prestress is required.

4. Beams—The investigation of the 36 in. (914 mm) deep inverted tee beam indicated typical strand savings of 18 to 25 percent for these members with the use of low-relaxation strands.

5. AASHTO girders—The AASHTO girder sections were investigated assuming a spacing of 6 ft 6 in. (2.0 m), with a 6½ in. (165 mm) thick composite slab. A few other girder spacings were also checked. In order to make comparisons, the moment requirements for Standard HS20-44 loading for the spans shown, including impact and load distribution, were converted to an equivalent required load per foot.

A summary of the computer study is shown in Table 5 and Fig. 5. The results indicate that strand savings of about 20 percent would be typical in the span ranges indicated. Based on losses calculated by Reference 4, when calculated by the method given in the AASHTO Specifications,[8] savings are somewhat less. An even greater overall savings is possible on some multi-lane bridges by increasing the spacing enough to reduce the total number of girders required.

Camber Comparisons

Camber in prestressed concrete members is caused by the prestressing force being applied eccentrically with respect to the center of gravity of the member. This is offset by the dead load

Table 1. Uniform load capacity (psf) for hollow-core slabs.

Member	Number of Strands	Strand Type	Initial Tension, percent	Span, ft							Max Span for Zero Deflection
				20	25	30	35	40	45	50	
4HC8	5	SR	70	221	125	72					30
		LR	70	221	125	73					31
			75	221	125	73					32
	6	SR	70	244	149	89	52				33
		LR	70	247	155	94	56				34
			75	247	155	94	57				35
	7	SR	70	250	171	104	64				36
		LR	70	253	183	113	71				36
			75	256	183	113	72				38
4HC12	6	SR	70				118	78	50		41
		LR	70				118	78	50		41
			75				118	78	50		43
	7	SR	70				133	95	63	40	44
		LR	70				136	98	66	42	45
			75				139	98	66	43	46
	8	SR	70				136	108	75	50	47
		LR	70				139	114	81	54	48
			75				142	117	81	55	50
4HC12 + 2-in. Topping	6	SR	70				123	68			37
		LR	70				124	75			38
			75				124	77			39
	7	SR	70				144	88	48		40
		LR	70				147	99	54		41
			75				150	100	63		42
	8	SR	70				147	107	63		43
		LR	70				150	121	73		43
			75				153	121	80		45

Note: 1 psf = 0.05 kPa; 1 ft = 0.305 m; 1 in. = 25.4 mm.

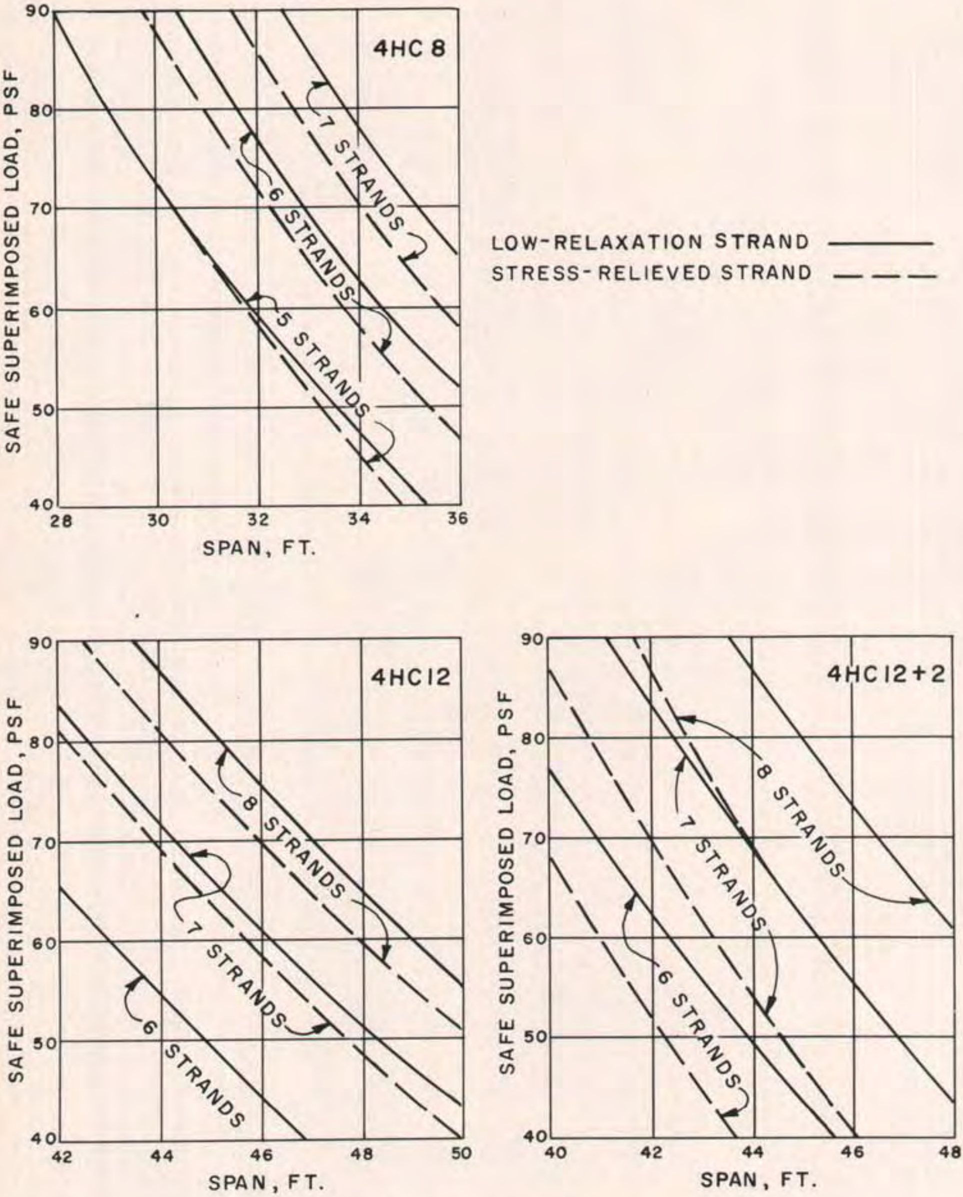


Fig. 1. Load capacity comparison (hollow-core slabs).

Table 2. Uniform load capacity (psf) for 24-in. (610 mm) deep double tees.

Member	Number of Strands	Strand Type	Initial Tension, percent	Span, ft								Max Span for Zero Deflection
				50	55	60	65	70	75	80		
8DT24	10	SR	70	101	74	56	42					68
		LR	70	101	76	57	43					69
			75	101	76	57	43					71
	12	SR	70			67	50	38				71
		LR	70			73	56	43				73
			75			73	56	43				76
	14	SR	70					44	34			74
		LR	70					50	39			76
			75					54	42			79
8DT24 + 2-in. Topping	8	SR	70	66	43							54
		LR	70	66	44							56
			75	66	44							58
	10	SR	70	89	57	36						58
		LR	70	93	66	44						60
			75	93	66	46						62
	12	SR	70			49	29					61
		LR	70			57	37					63
			75			63	44					65
8LDT24 (Lightweight)	10	SR	70	109	82	63	48	38	29			74
		LR	70	111	86	68	53	41	32			76
			75	111	86	68	53	41	32			78
	12	SR	70				59	45	34			78
		LR	70				64	50	38			80
			75				66	53	42			82
	14	SR	70						42	32		81
		LR	70						46	36		83
			75						52	42		85

Note 1 psf = 0.05 kPa, 1 ft = 0.305 m; 1 in. = 25.4 mm.

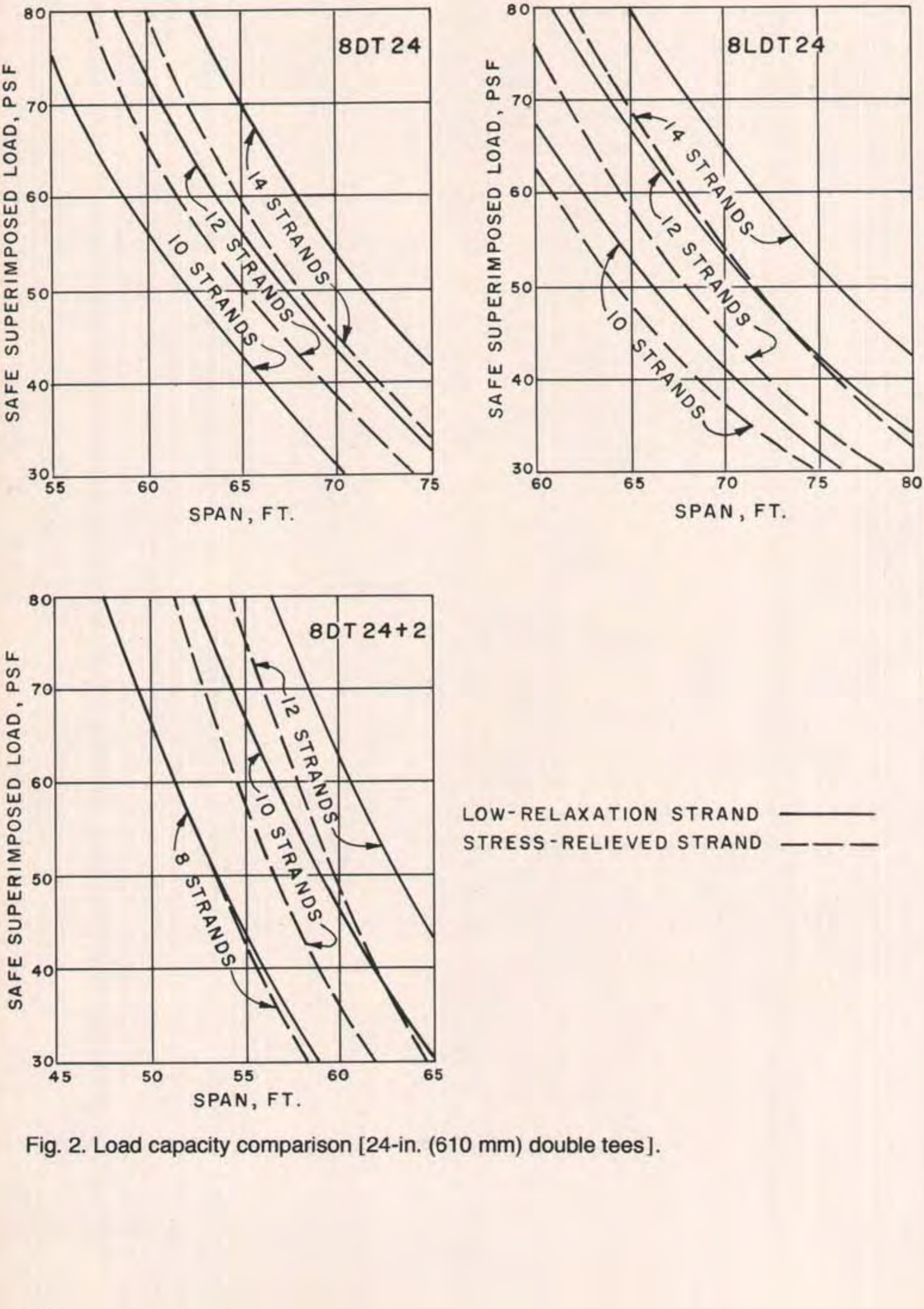
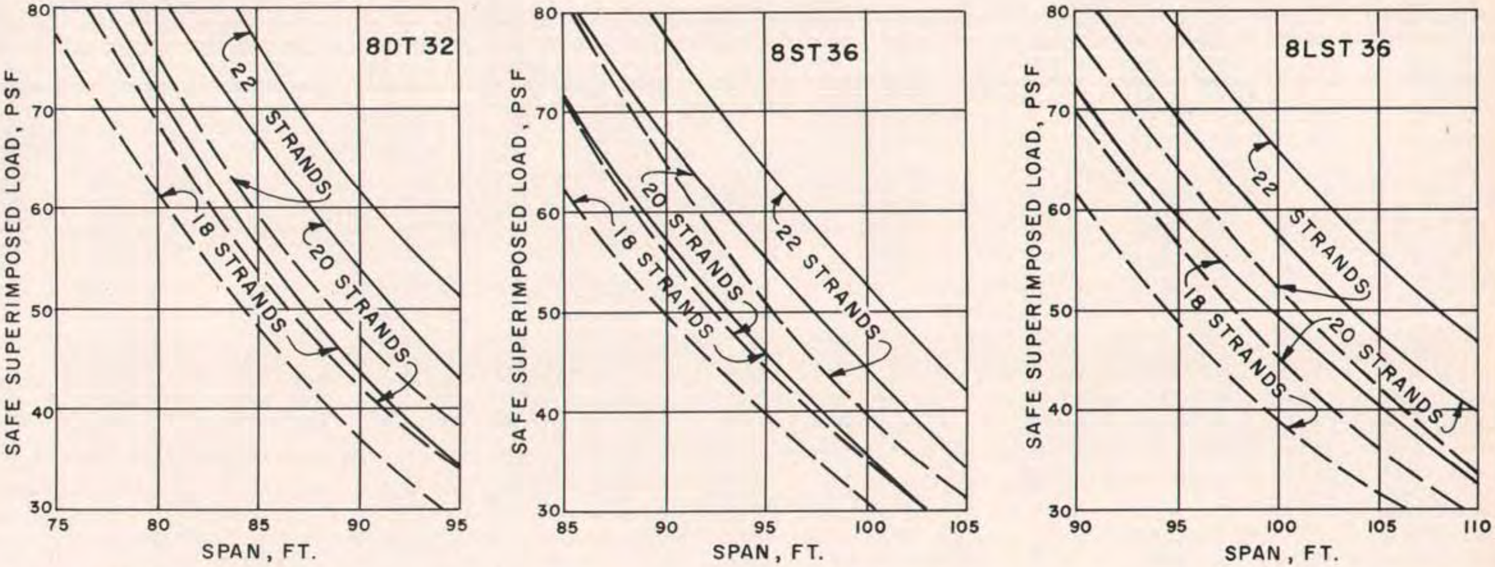


Fig. 2. Load capacity comparison [24-in. (610 mm) double tees].

Table 3. Uniform load capacity (psf) for long span members.

Member	Number of Strands	Strand Type	Initial Tension, percent	Span, ft										Max Span for Zero Deflection
				65	70	75	80	85	90	95	100	105	110	
8DT32	18	SR	70	127	99	77	62	48						84
		LR	70	138	109	87	70	56						86
			75	139	112	90	72	57						89
	20	SR	70	140	111	87	68	54	43					86
		LR	70	153	122	97	77	62	50					88
			75	157	127	103	83	67	54					92
	22	SR	70			97	76	59	47	37				88
		LR	70			107	85	68	55	45				90
			75			116	95	77	62	50				94
8ST36	18	SR	70				80	62	50	40	31			93
		LR	70				89	71	57	45	35			96
			75				89	72	57	45	35			100
	20	SR	70						56	49	36			96
		LR	70						64	57	43			99
			75						68	60	44			103
	22	SR	70							51	40	31		99
		LR	70							58	47	38		102
			75							64	52	42		106
8LST36	18	SR	70							49	39	32		103
		LR	70							55	45	38		106
			75							60	50	40		110
	20	SR	70								46	36		106
		LR	70								52	42		109
			75								58	48		113
	22	SR	70									42	34	109
		LR	70									49	39	112
			75									56	47	116

Note: 1 psf = 0.05 kPa; 1 ft = 0.305 m.



LOW-RELAXATION STRAND ————

STRESS-RELIEVED STRAND — — —

Fig. 3. Load capacity comparison (long span members).

Table 4. Uniform load capacity (plf) for inverted tee beam.

Member	Number of Strands	Strand Type	Initial Tension, percent	Span, ft 24	26	28	30	32	34	36	38	40
Inverted Tee Beam—24IT36	12	SR	70	7711	6430	5471	4698	4065	3541	3101	2729	2412
		LR	70	8207	6846	5831	5012	4343	3787	3322	2929	2585
			75	8694	7269	6196	5330	4622	4034	3542	3126	2771
	14	SR	70	8547	7154	6097	5244	4546	3968	3483	3073	2723
		LR	70	9103	7623	6503	5599	4860	4247	3733	3298	2927
			75	9658	8109	6922	5964	5180	4530	3986	3525	3132
	16	SR	70		7730	6594	5677	4927	4306	3785	3344	2968
		LR	70		8241	7036	6064	5269	4610	4057	3590	3190
			75		8777	7498	6466	5622	4922	4336	3839	3416
	18	SR	70		8466	7217	6210	5385	4702	4129	3649	3244
		LR	70		8978	7658	6594	5725	5015	4420	3916	3486
			75		9669	8254	7113	6179	5405	4756	4207	3738
	20	SR	70			7812	6728	5840	5105	4489	3967	3522
		LR	70			8296	7149	6211	5433	4781	4230	3759
			75			8891	7668	6666	5837	5141	4553	4051

Note: 1 psf = 0.05 kPa; 1 ft = 0.305 m.

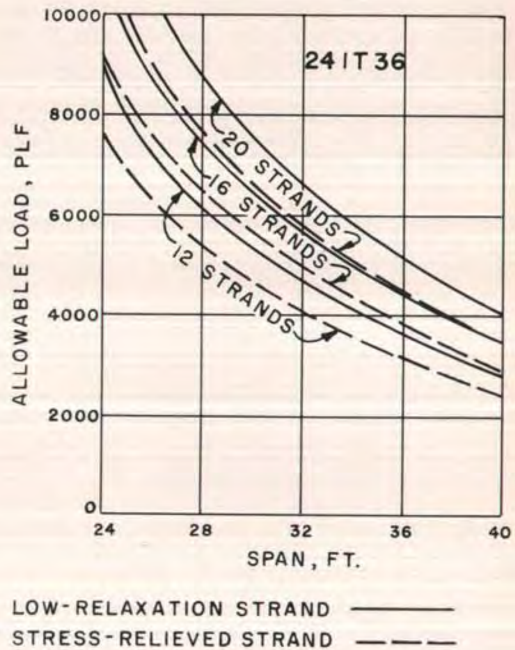


Fig. 4. Capacity of Type IV AASHTO girder compared with highway load requirement.

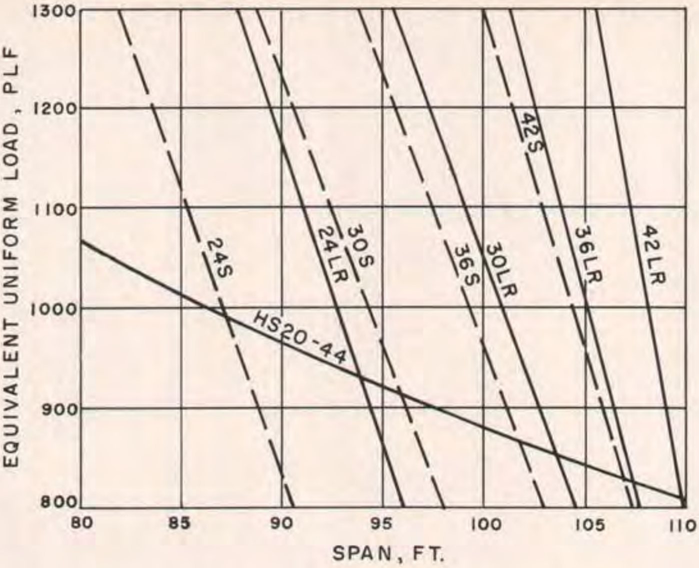


Fig. 5. Capacity of Type IV AASHTO girder compared with highway load requirement.

deflection of the member. Creep of the concrete causes each of these components to increase with age, but because of losses, the prestress force is being constantly reduced, so the downward (deflection) component increases faster than the upward (camber) component. With low-relaxation strands, there is less difference in the rate of increase.

With proper plant quality control over such items as concrete release strength, strand placement (especially when strands are depressed at midspan) and initial tension, the camber at the time of release can be predicted with reasonable accuracy. There are many more and less easily controlled factors which influence long-time camber, however, and predictions of what the camber will be at critical times, such as at the time of erection, are at best approximations.

The computer program LODTAB uses the equations suggested by Martin[9] for predicting the change in camber over time. His paper is also the basis for camber predictions used in the PCI Design Handbook.

In general, most precast, prestressed deck members used at their optimum span and prestress level will show a camber increase for the first few months, and then a gradual decrease for the remainder of their life. This decrease levels off after a year or so and then there is usually no discernable change. For roof members on "flat" roofs it is, of course, desirable to have some upward camber remaining in the member so that ponding is prevented.

Thus, it is common and desirable practice to limit the span to lengths that indicate no worse than level at the "final" condition. When low-relaxation strand is used, this will permit somewhat longer spans for deck members before this limiting criterion is reached. Increase of initial tension further increases the span range. Tables 1 through 5 show these suggested limits,

Table 5. Uniform load capacity (plf) for AASHTO girders 6 ft 6 in. (2.0 m) spacing—6½ in. (165 mm) thick composite deck.

Number of Strands	Strand Type	Initial Tension, percent	Span, ft							
			70	75	80	85	90	95	100	105
24	SR	70	2529	1973	1519	1142	826	559		
	LR	70	2702	2211	1750	1330	975	674		
		75	2702	2211	1808	1475	1179	857		
30	SR	70	3229	2587	2061	1626	1261	951	689	
	LR	70	3574	2891	2331	1868	1480	1152	871	
		75	3587	2981	2486	2075	1691	1341	1042	
33	SR	70	3569	2857	2280	1820	1435	1110	832	593
	LR	70	3903	3155	2565	2076	1666	1320	1024	770
		75	3982	3325	2788	2330	1893	1523	1207	935
36	SR	70	3898	3143	2525	2014	1591	1250	959	709
	LR	70	4256	3455	2799	2262	1833	1470	1161	894
		75	4348	3645	3069	2584	2093	1685	1354	1069
39	SR	70	4302	3496	2835	2288	1829	1441	1114	851
	LR	70	4689	3833	3131	2550	2063	1652	1326	1045
		75	4762	4005	3385	2872	2379	1935	1555	1213
42	SR	70	4705	3847	3144	2561	2073	1660	1307	1004
	LR	70	5121	4209	3462	2843	2325	1886	1511	1178
		75	5170	4360	3698	3148	2664	2191	1786	1328
45	SR	70	5009	4111	3376	2767	2257	1825	1456	1058
	LR	70	5447	4492	3711	3064	2521	2062	1670	1169
		75	5502	4650	3952	3374	2879	2383	1942	1319

Note: 1 psf = 0.05 kPa; 1 ft = 0.305 m.

based on the assumptions described earlier.

It should be noted that it can be very dangerous to depend on camber for roof drainage. A positive slope of at least 1:100 (and preferably more) should be provided in designing any roof system.

For a given number of strands and prestress level, it is apparent that the use of low-relaxation strand will result in more camber. However, the previous section showed that for the same load capacity, in many cases fewer strands are required, even without an increase in initial tension. Doing this will result in less camber of the members, and the predictions are likely to be more accurate.

Release Strength

Strand tensioned to 75 percent of ultimate will obviously require the concrete at time of transfer to be of higher strength than the same number of strand tensioned to 70 percent of ultimate, under the criteria imposed by codes and specifications. However, as with cambers, equivalent load capacity requires fewer strands, often without requiring increased initial tension, so release strength requirements are less, resulting in further savings. In beams with straight strands, it is common practice to reinforce for end tension at release. With fewer strands for equivalent capacity, less reinforcement is required.

Effect of Mixing Low-Relaxation Strand With Ordinary Strand

If the decision is made to use low-relaxation strand, and if the plant is manufacturing products designed for low-relaxation steel, it is highly recommended that the prestressing plant convert to it for all products. This would avoid the possibility of inadvertent use of ordinary strand in a member designed for low-relaxation strand. However, when using more than one strand supplier, occasions may arise when the two types of strands would be mixed in a member.

Some specifiers have expressed a concern that the different properties would have some detrimental effects with regard to possible lateral deflection, cambers or torsion even if they were designed for ordinary stress-relieved strand. The calculations in the Appendix show that any such effects are negligible. The member used in the example represents the most extreme case that could be found among standard products. In fact, the effects shown are probably even more severe than would actually occur, since the difference in prestressing force occurs over time and creep would tend to neutralize the differences.

Optimizing Strand Usage

In double tees, additional strand savings could be realized by "unbalancing" the strand patterns. If only even numbers of strands are used, statistically 50 percent of the members would have one more strand than required. Producers have been reluctant to use odd numbers of strands, such as six in one stem and seven in the other, because of the same potential effects illustrated in the calculations of the previous section.

In the case of unbalanced strand, the maximum force difference, P, would be at the end at release. If a ½ in. diameter, 270 ksi (13 mm, 1860 MPa) strand were tensioned to 75 percent of ultimate, this difference (neglecting losses which occur before release) would be:

$$P = (0.153)(270)(0.75) = 31 \text{ kips } (138 \text{ kN})$$

using a modulus of elasticity at release of 3300 ksi (2.3×10^3 MPa), corresponding to a release strength of approximately 3000 psi (21 MPa), the maximum lateral sweep (LS) would be (see Appendix):

$$LS = 0.050\,(31.0/16.8)\,(2150/3300) = 0.060 \text{ in. } (1.5 \text{ mm})$$

The torsional stress (TS) would be:

$$TS = 5.6\,(31.0/16.8) = 10.3 \text{ psi } (71 \text{ kPa})$$

and the flange tension (FT):

$$FT = 92\,(31.0/16.8) = 170 \text{ psi } (1170 \text{ kPa})$$

This is less than the cracking stress, even when the compression caused by gravity loads is not included.

CONCLUSIONS

The analyses made in this paper indicate that the use of low-relaxation strand can result in significant strand savings for virtually all types of precast, prestressed standard products for designs approaching maximum capability. This is especially true in longer, heavier structural members. For example, the savings will be less with hollow-core slabs than with bridge girders. Low-relaxation strand can also provide improvements in deflection and cracking control.

It was also shown that low-relaxation strand can be mixed with stress-relieved strand in a design based on stress-relieved strand properties without harmful effects. With the much improved properties of low-relaxation strand over stress-relieved strand, and with the price of it being competitive with stress-relieved, low-relaxation strand will undoubtedly become the standard of the industry.

ACKNOWLEDGMENT

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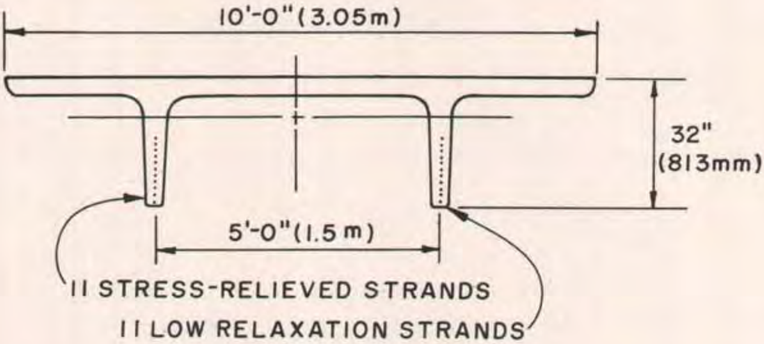
Note: A design example is provided in the Appendix on the following two pages.

APPENDIX — DESIGN EXAMPLE

This design example shows the effect of mixing low-relaxation strand and stress-relieved strand. The effect would be greatest in a double-tee member where the maximum number of strands were spaced the maximum lateral distance apart. From the PCI Design Handbook, select a 10DT32 section with 22 ½-in. (12.7 mm) diameter, 270 ksi (1860 MPa) strands.



The section properties and strand details are as follows:

I_x = 626,791 in.^{4} (1.03 x 10^{10} mm^4)

I_y = 59,720 in.^{4} (9.79 x 10^8 mm^4)

Strand eccentricity:

e_e = 5.57 in. (141 mm)

e_c = 17.48 in. (444 mm)

e = 11.91 in. (303 mm)

Stress to 70 percent ultimate:

0.70 x 270 = 189 ksi (1303 MPa)

Strand area per stem:

11 x 0.153 = 1.683 in.^{2} (109 mm^2)

Assume a maximum prestress loss (according to the recommendations in Reference 6).

Final strand stress:

Low-relaxation strand = 189 − 40 = 149 ksi

Stress-relieved strand = 189 − 50 = 139 ksi

= 10 ksi (69 MPa)

The difference in the final prestress force is:

P = 10 x 1.68 = 16.8 kips (74.7 kN)

Assume that:

f'_c = 5000 psi (34.5 MPa)

E_c = 4300 ksi (3.0 x 10^4 MPa)

To account for creep, use the long-term value:

$$E_{ct} = \frac{E_c}{2} = 2150 \text{ ksi } (1.5 \times 10^4 \text{ MPa})$$

Span = 86 ft (26.2 m)

1. Potential lateral deflection (sweep):

$$\frac{Pel^2}{8EI} = \frac{16.8\,(30)\,(86 \times 12)^2}{8\,(2150)\,(626{,}791)} = 0.05 \text{ in. } (1.3 \text{ mm})$$

which is a negligible quantity.

2. Potential torsional stresses:

The theoretical difference in upward camber of each stem is:

$$\Delta = \frac{Pe_e l^2}{8EI} + \frac{Pe' l^2}{12EI}$$

in which

$$\frac{Pl^2}{EI} = \frac{e_e}{8} + \frac{e'}{12} \text{ and } I = \frac{I_y}{2}$$

Therefore:

$$\Delta = \frac{16.8\,(86 \times 12)^2}{2{,}150 \times 29{,}860}\left[\frac{5.57}{8} + \frac{11.9}{12}\right]$$
$$= 0.471 \text{ in. (12 mm)}$$

The equivalent uniform load to cause the same deflection is found from the equation:

$$\Delta = \frac{5wl^4}{384EI}$$

or

$$w = \frac{384EI\Delta}{5l^4}$$
$$= \frac{384\,(2{,}150)\,(29{,}860)\,(0.471)}{5\,(86 \times 12)^4}$$
$$= 24.6 \text{ lb per ft (359 N/m)}$$

from which the weight

$$W = 24.6 \times 86$$
$$= 2{,}113 \text{ lb (9,345 N)}$$

The torsional moment equals:

$$T = 2{,}113 \times 30$$
$$= 63{,}390 \text{ in.-lb}$$

The polar moment of inertia is found from the sum:

$$J = I_x + I_y$$
$$= 626{,}791 + 59{,}720$$
$$= 686{,}511 \text{ in.}^4$$

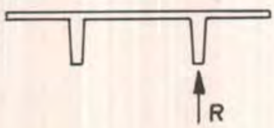
The distance from the neutral axis is:

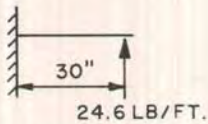
$$c = b/2 = 60 \text{ in. (1524 mm)}$$

The torsional stress is obtained from:

$$\frac{Tc}{J} = \frac{63{,}390 \times 60}{686.511}$$
$$= 5.6 \text{ psi (38.6 kPa)}$$

which is obviously negligible.





3. Potential flange stress

With reference to the sketch:

$$M = 24.6\,(30) = 738 \text{ in.-lb per ft}$$

Section modulus of flange:

$$\frac{bd^2}{6} = \frac{12\,(2)^2}{6} = 8 \text{ in.}^3 \text{ per ft}$$

Maximum tensile stress:

$$\frac{M}{S} = \frac{738}{8} = 92 \text{ psi (634 kPa)}$$

The computed tensile stress is much less than that which would cause cracking even neglecting compression from gravity loads.

* * *

NOTE: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by March 1, 1984.