Overload Capacity—Prestressed Compared with Reinforced Concrete

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If prestressed concrete is cheaper than reinforced concrete in a particular case, is it a true economy to use it or does the reinforced concrete have a greater overload capacity? This paper compares the overload capacities of simple span bridge girders in both prestressed and reinforced concrete. Ultimate strength calculations are based on the plastic theory for both types of construction. References are given to support formulas used to calculate ultimate strengths.

In most cases the girders compared are found in bridges designed and built by the California Division of Highways. Three ranges of span lengths are considered:—under 60 feet, 60–80 feet, and 80–120 feet.

● IT has been said that prestressed concrete does not have the overload capacity that conventional reinforced concrete has. The purpose of this paper is to investigate this contention by comparing the overload capacities of both prestressed and reinforced concrete bridge girders that have been designed and built in the state of California. Since load tests were not performed on any of these structures, it is necessary to calculate an ultimate strength by means of a formula known to give reasonably accurate results and based on assumptions generally accepted by the engineering profession. It is known that in the ultimate range, prestressed concrete acts just like conventional reinforced concrete, if the prestressing steel is grouted in (*1*). It is reasonable, therefore, to use the same formula to calculate the ultimate moments for both prestressed and reinforced concrete. Based on the plastic theory, a generally accepted formula for ultimate moment is $M_u = 0.9\ A_s f_s' d$ (*2*).[1] This is the formula recommended by the Bureau of Public Roads and used by the California Bridge Department (*3*, *4*).

Only simple spans are considered in this report. Although many continuous reinforced concrete bridges have been built, California has had limited experience with continuous prestressed bridges. Also, there is little published information on the behavior of continuous prestressed structures at or near failure. From the scant information available, it is probable that a continuous prestressed concrete structure would form plastic hinges and otherwise act like reinforced concrete in the ultimate range. For this reason it is believed that the relationships found for ultimate capacity of simple span reinforced concrete and prestressed concrete bridges would hold for continuous structures as well.

A common misconception seems to be that a reinforced concrete member collapses at a much greater moment than that which causes yield in the steel. Since the ultimate strength of intermediate grade steel is about twice the yield, it seems reasonable to think that the ultimate load (collapsing load) a reinforced concrete member can carry is about twice the yield load. This, unfortunately, is not generally so. Because of the shape of the stress-strain curve for this type of steel, so much plastic strain occurs at the yield stress that the concrete usually fails in compression with no significant increase in load (*3*, *5*, *6*, *7*, *8*, *9*). In the case of very lightly reinforced beams, the steel may become work-hardened before the concrete crushes and so carry considerably more moment than that producing the yield stress (*10*). Bridge girders, however, do not fall into this classification, so for the purposes of this paper it may be assumed that the yield strength of the steel determines

[1] Except where otherwise noted, the notation used is that found in references 3 and 4.

the load carrying capacity of the reinforced concrete bridge girder.

Because of the shape of the stress-strain curve for the steel used in prestressed concrete however, failure occurs at the ultimate strength rather than at yield (*5*). According to the plastic theory, although stresses are not linear at rupture, strains are. Concrete fails when its strain has reached a limiting value (*2*, *8*). Whether medium grade or high tensile steel (prestressed or not) is used, the concrete will crush when the strain in the steel is sufficient to cause the concrete strain to reach the point of failure (*3*, *8*). In the case of over-reinforced prestressed concrete beams, the concrete will crush before the prestressing steel has reached the yield point. For this reason the B.P.R. criteria use 0.8 f_c' instead of 1.0 f_c' in determining what constitutes balanced reinforcement. This has the effect of increasing the factor of safety of this class of beams (*3*).

Prestressed beams in which the prestressing steel is not grouted in are generally believed to have a lower ultimate strength than those in which the steel is fully grouted. The amount of this decrease in strength is not completely known. Walley (*11*) shows test results which indicate that a non-grouted beam is about 75 percent as strong as that same beam would be if the prestressing steel were fully grouted in after prestressing. None of the beams considered in this report are non-grouted.

In the past four years the California Division of Highways has designed and built many prestressed and reinforced concrete highway bridges ranging in span from 30 to 120 feet. In the accompanying tables, the safety factors of representative prestressed and reinforced concrete bridges are compared. For purposes of comparison, the reinforcing steel in the reinforced concrete structures is assumed to have a yield stress of 40,000 psi and a working stress of 20,000 psi. None of the reinforced concrete bridges uses compressive reinforcement.

Present California design specifications require that the working force (P_W) for prestressed concrete bridges represent a stress in the prestressing steel of not more than 60 percent of the ultimate. Therefore, 0.9 $A_s f_s' d$ can be written 0.9 $A_s f_s d/0.6$ which equals 1.5 $A_s f_s d$; but $A_s f_s$ = working force, and $M_u = 1.5\, P_w d$. For beams not over-reinforced, the ultimate moment does not depend on the ultimate strength of the steel, but on the percent of the ultimate that is used as a working stress. In this paper it is assumed that in all cases $f_s = 0.6\, f_s'$.

When the prestressing elements are bonded to the concrete, the reinforcement is assumed "balanced" (i. e., where the steel and concrete fail simultaneously) if:

$$p_b = 0.23\, \frac{0.8 f_c'}{f_s'}\,.$$

Where p is greater than p_b, $M_u = 0.9 \sqrt{a_{bs} a_s}\; f_s' d$. The prestressed cored slab or Eureka Slough Alternative B in Table 1 is the only over-reinforced section included in this report. The type of failure characteristic of over-reinforced members is recognized to be undesirable and over-reinforced prestressed concrete is avoided wherever possible.

In all the bridges listed in the following tables, the beams—both prestressed and reinforced—are assumed to be properly reinforced against shear, and failure occurs by bending only. Reinforced concrete is assumed to fail at the yield stress of the steel, and prestressed concrete at the ultimate strength of the prestressing steel. M_d is the total design dead load moment, M_l is the total design live load plus impact moment, and M_t is the total design moment. In all cases live load is distributed among the girders in accordance with the applicable AASHO specifications.

$$\text{Total Safety Factor} = \frac{M_u}{M_t}\,;$$

$$\text{Live Load Safety Factor} = \frac{M_u - M_d}{M_l}$$

In Table 1 are shown five prestressed structures of spans less than 60 feet. All of these are precast elements. Eureka Slough Alternative B is a pretensioned cored slab. Arno Road is a post-tensioned T-beam structure, while the other three are post-tensioned inverted channel sections. The last one in this table is an inverted channel section that has been developed as a standard by the Bridge Department.

Table 2 shows six reinforced concrete structures of less than 60-foot span. Eureka Slough

TABLE 1
PRESTRESSED SPANS LESS THAN 60 FEET

Name	Type	Span Length	Total Safety Factory	Live Load Safety Factor
		ft.		
Eureka Slough alternative B	Pretensioned cored slab	30	2.64	3.97
Dry Creek Canal	Inverted channel	44	2.20	2.95
Rte 20/1 Sep.	Inverted channel	45	1.92	2.60
Arno Rd. O.C.	T-beam	58	1.98	2.70
Standard	Inverted channel	45	2.26	3.24

TABLE 2
REINFORCED CONCRETE SPANS LESS THAN 60 FEET

Name	Type	Span Length	Total Safety Factor	Live Load Safety Factor
		ft.		
Eureka Slough alternative A	Inverted channel	30	2.57	3.99
Slauson Ave. U. C.	Slab	38	2.02	3.45
Union Oil O.H.	Cored slab	45	2.17	3.91
L. A. Riv. Br. and O. H. @ Aliso St.	T-beam	46	1.92	2.65
Meeker Rd. U.C.	Box girder	53	1.76	2.37
Garvey Ave. O.R.	Box girder	56	1.82	2.42

Alternative A is a precast channel section; all the rest are cast-in-place. The two Eureka slough alternative structures were shown on the bridge plans to invite competitive bidding, and the contractor elected the prestressed Alternative B.

Note that in this span range the average total safety factor is 2.20 for the prestressed structures and 2.05 for the reinforced concrete The average live load safety factor is 3.09 for the prestressed spans and 3.13 for the reinforced concrete.

Table 3 shows five prestressed concrete bridges having span lengths between 60 and 80 feet. All of these are precast, post-tensioned modified T sections with a 1- to 2-foot section

TABLE 3
PRESTRESSED SPANS 60-80 FEET

Name	Type	Span Length	Total Safety Factor	Live Load Safety Factor
		ft.		
Weber Ave. O.C.	T-beam	67	1.87	2.58
Rte 107/5 Sep.	T-beam	67	1.83	2.49
L. A. Riv. Br. and O.H. @ Aliso St.	T-beam	78	1.96	3.04
Hercules Sep. and O.H.	T-beam	78	1.84	2.67
Richardson Bay Br.	T-beam	78	1.95	2.96

TABLE 4
REINFORCED CONCRETE SPANS 60-80 FEET

Name	Type	Span Length	Total Safety Factor	Live Load Safety Factor
		ft.		
American Riv. Br. @ Four Oaks	T-beam	60	1.94	2.66
104th St. U.C.	Box girder	61	2.08	3.05
Lexington Ave. O.C.	Box girder	62	1.85	2.58
Bonsall Ave. U.C.	Box girder	62	1.90	2.75
Edenhurst Ave. U.C.	Box girder	65	2.01	2.85
Weldon U.C.	Box girder	75	2.08	3.55

of slab cast in place between the girder flanges. Three of these bridges are completed and the other two are under construction. The girders are all very similar in appearance and differ mainly in depth and spacing. Girder depth varies between 3 and 4½ feet, and the spacing between 3 and 6 feet.

Weber Avenue is the first prestressed concrete highway bridge built in California. It consists of 10 girders 3 feet deep spaced at about 37-in. centers. Although the bridge is 22 feet between curbs, it is classed as a single lane structure. When the live load is distributed over all the girders in determining safety factors (as was permissible when this bridge was built), the total safety factor becomes 2.34, and the live load safety factor becomes 4.04.

In Table 4 are six reinforced concrete bridges in the 60 to 80-foot span range. All of these are cast-in-place structures. Structure depth is not critical and girder spacing is 7 feet or more. These structures are conventional in every respect and represent good design practice.

In this span range the average total safety factor is 1.89 for the prestressed concrete bridges, and 1.98 for the reinforced concrete. The average live load safety factor is 2.75 for the prestressed and 2.91 for the reinforced concrete.

Table 5 contains four prestressed bridges in the 80- to 120-foot range. Of these, Balboa Boulevard and Eureka Slough are precast modified T-beams. Big Dalton Wash is a cast-in-place box girder, and Scott River a cast-in-place T-beam bridge. The Scott River Bridge is the longest prestressed bridge yet built in California. Because it is only 28 feet between curbs, it was designed as a unit rather than

TABLE 5
PRESTRESSED SPANS 80-120 FEET

Name	Type	Span Length	Total Safety Factor	Live Load Safety Factor
		ft.		
Eureka Slough	T-beam	105	1.89	3.43
Big Dalton Wash	Box girder	114	1.83	3.36
Balboa Blvd. U.C.	T-beam	115	2.04	3.92
Scott River Br. (Horn Lane)	T-beam	120	1.82	3.84

TABLE 6
REINFORCED CONCRETE SPANS 80-120 FEET

Name	Type	Span Length	Total Safety Factor	Live Load Safety Factor
		ft.		
Third St. U.C.	Box girder	81	1.84	2.79
Ninth St. O.H.	Box girder	81	1.81	2.76
Slauson Ave. U.C.	Box girder	82	1.97	3.14
Chapman Ave. O.C.	Box girder	85	1.88	2.94
Rte 26/170 Sep.	Box girder	104	2.06	3.70
Big Dalton Wash	Box girder	114	1.96	3.68

as a series of individual girders. The girder spacing of these bridges varied between 63½ in. for Eureka Slough and 96 in. for Scott River. Balboa Boulevard has a 6-inch slab cast in place on top of the 3-foot wide top flange. These girders are 5½ feet deep and are spaced at about 7-foot centers.

In Table 6 are shown six cast-in-place, reinforced concrete box girders. This 80 to 120-foot range is beyond the economical limit for reinforced concrete simple span T beams. The Big Dalton Wash structure may be compared with the bridge of the same name in Table 5. The structures carry the freeway and two frontage roads over Big Dalton Wash. Because of clearance requirements, 75 in. were available for the freeway bridge (in Table 6) and only 52 in. for the frontage roads (Table 5). This is an example of the amount of structure depth it is possible to save in the longer spans by the use of prestressed concrete.

The average total safety factor is 1.90 for the prestressed concrete bridges and 1.92 for the reinforced concrete. The average live load safety factor is 3.64 for the prestressed bridges and 3.17 for the reinforced concrete.

The average total safety factor for the 14 prestressed concrete bridges is 2.00, and for the 18 reinforced concrete bridges it is 1.98. The average live load safety factor is 3.12 for the prestressed concrete and 3.07 for the reinforced. The lowest total safety factors are 1.82 for the prestressed, and 1.76 for the reinforced concrete. The lowest live load safety factors are 2.49 for the prestressed and 2.37 for the reinforced concrete.

Based on the assumptions used in compiling these tables, it can be seen that there is generally very little difference in the overload capacities of prestressed or reinforced concrete bridges as built in California. Since both design systems have substantially the same reserve strength, the designer may feel free to choose either, basing his selection upon other factors which may show a preference for either the prestressed or reinforced concrete.

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