Flexural Design Considerations for Prestressed Concrete Girders Using Stainless Steel Strands

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Several articles by Dr. Oguzhan Bayrak in previous issues of *ASPIRE®* have addressed topics of structural behavior and redundancy. In the article published in the Winter 2021 issue, Bayrak discussed the considerations that should be made to incorporate new materials into design specifications and how those new materials may affect the behavior of members. New materials may require the engineer to adapt to a new philosophical approach to design. This is the case when prestressed concrete members are designed with stainless steel prestressing strand. Stainless steel strand is an emerging type of strand that is desirable in concrete members in extremely aggressive environments because it is highly resistant to corrosion. This property leads to a longer service life, lower maintenance costs, and fewer disruptions to the public. Unlike conventional carbon steel strand, stainless steel strand is not at risk for rust from environmental exposure while stored at the casting yard. Although the corrosion resistance of stainless steel strand is superior to that of carbon steel strand, the tensile strength, total elongation, and modulus of elasticity of stainless steel strand are lower, which influences the flexural behavior of members. In December 2020, a report was published for a Florida Department of Transportation (FDOT)–sponsored research project that investigated the use of 0.6-in.-diameter stainless steel strands in prestressed concrete I-girders.[1] This article discusses selected key findings from the project, special behavior of stainless steel strand, and important design considerations when designing with stainless steel strand.

Mechanical Properties

The mechanical properties of the strands are a key factor in the flexural behavior of a prestressed concrete girder. Stainless steel strand is relatively new to the construction industry. ASTM A1114, *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*,[2] was published in April 2020. **Table 1** shows guaranteed mechanical properties of 0.62-in.-diameter stainless steel and carbon steel strands specified in ASTM A1114[2] and ASTM A416,[3] respectively. The guaranteed tensile strength of stainless steel strand is 88.9% of that of carbon steel strand, and the guaranteed tensile strain of stainless steel strand is 0.014, which is only 40% of the value for carbon steel strand. These values are evident in **Fig. 1**, which superimposes a typical stress-strain curve for carbon steel strand onto a stress-strain curve of stainless steel strand based on experimental tests of specimens from two spools of strand by Al-Kaimakchi and Rambo-Roddenberry.[4] Also, tensile tests revealed that the elastic modulus of stainless steel strand from the two spools was between 23,900 and 25,800 ksi; by comparison, the nominal elastic modulus for carbon steel strand is 28,500 ksi.

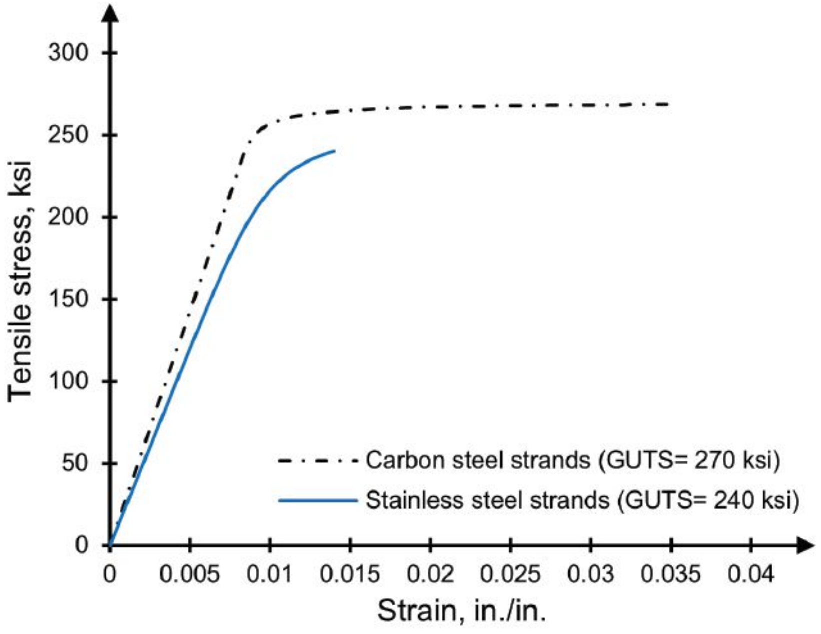
Experimental Behavior of Girders with Stainless Steel Strands

A prestressed concrete girder can fail in flexure by either crushing of concrete in the compression zone or rupture of strands in the tension zone. Because of the low ultimate strain (total elongation) of stainless steel strand (Fig. 1 and Table 1), some girder designs are expected to fail due to rupture of the strands before the concrete in the compression zone reaches its ultimate strain. This expectation is contrary to the design philosophy for girders with carbon steel strands where the girders are designed to fail due to crushing of concrete after yielding of the strands.

Full-scale flexural tests on five 42-ft-long AASHTO Type II girders (design concrete compressive strength of 8.5 ksi), all with an 8-in.-thick, 24-in.-wide composite concrete deck slab (design concrete compressive strength of 4.5 ksi) and prestressed with stainless steel strands, were conducted for FDOT. The number of strands (reinforcement ratio) was the only design variable.[1] Each strand was tensioned at the casting yard to an initial force of 36 kip, which was 65% of the guaranteed ultimate tensile strength. As anticipated, the girders

Table 1. Specified minimum mechanical properties of 0.62-in.-diameter strands

Mechanical properties	Stainless steel strand ASTM A1114[2]	Carbon steel strand ASTM A416[3]
Diameter, in.	0.62	0.62
Area, in.[2]	0.231	0.231
Yield strength, lbf	49,860	56,520
Breaking strength, lbf	55,400	62,800
Total elongation	1.4%	3.5%



Note: GUTS = guaranteed ultimate tensile strength.

Figure 1. Comparison of stress-strain curves of stainless steel and carbon steel strands. All Figures: Anwer Al-Kaimakchi.

failed due to rupture of strands while the concrete compression zone was still intact (**Fig. 2**). Experimental results showed that girders with larger numbers of stainless steel strands:

- exhibited larger deflections and ultimate loads at failure,
- had higher concrete top-fiber strains at failure, and
- had more flexural cracks and smaller crack spacings.

Before failure, the girders exhibited noticeable deflection and widespread cracking, both of which are desirable before failure.

Parametric Study of Behavior of Girders with Stainless Steel Strands

From the results of a parametric study (using 7 to 21 strands) conducted with the same composite girder cross section that had been used for the FDOT research project, Al-Kaimakchi and Rambo-Roddenberry determined relationships between the number of stainless steel strands (reinforcement ratio), flexural resistance, ultimate curvature, and ultimate deflection for concrete I-girders (**Fig. 3**).[4] The left part of Fig. 3 shows that the factored flexural resistance (ϕM_n) of the girder increases with an increase in the number of stainless steel strands. A balanced failure (simultaneous crushing of concrete and rupture of the stainless steel strands) occurs at the number of strands represented by the red triangle. Extending a solid horizontal red line to the other graphs, the designs above the solid red line fail by crushing of concrete (compression controlled) and designs below the red line fail by rupture of the stainless steel strands (tension controlled).

Figure 2. In a research study conducted for Florida Department of Transportation, 42-ft-long AASHTO Type II girders, all with 8-in.-thick, 24-in.-wide composite deck slabs and prestressed with stainless steel strands, were tested in flexure.[1] This photo shows a girder with nine strands immediately after failure by strand rupture. Girders with seven and eleven strands failed in the same manner.

Figure 3 (middle and right) shows that when a girder is expected to fail due to rupture of strands (below the red line), ultimate curvature and deflection increase as the number of stainless steel strands increases. Based on the relationship in **Eq. (1)**, the concrete top-fiber strain at failure ε_c also increases as the number of strands increases. Continuing to increase the number of stainless steel strands will eventually result in simultaneous failure (red triangle) of both concrete in the compression zone and the stainless steel prestressing strands in the tension zone. As mentioned previously, increasing the number of strands beyond the balanced failure point results in failure by crushing of the concrete. When the girder is expected to fail due to crushing of concrete, ultimate curvature and ultimate deflection decrease with an increase in the number of stainless steel strands because the net tensile strain decreases (Eq. [1]).

Ultimate curvature (curvature at failure):

$$\phi = \frac{\varepsilon_c}{c} = \frac{NTS}{d-c} \qquad (1)$$

where

ε_c = concrete top-fiber strain at failure

c = depth of neutral axis

NTS = net tensile strain in the bottom row of strands

d = distance from the top fiber to the bottom row of strands

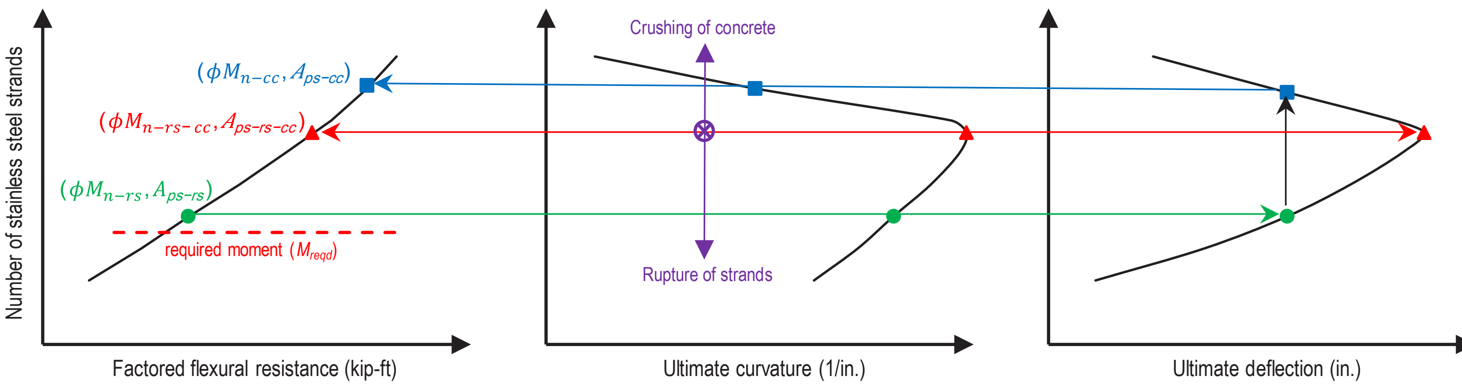


Figure 3. Behavior of a prestressed concrete girder with stainless steel strands: flexure (left), curvature (middle), and deformation (right).

It is significant to note that for all of the designs represented in Fig. 3, *NTS* is greater than 0.005, which is the lower limit of net tensile strength for which sections can be considered to be tension-controlled in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[5] That means all the designs in this figure are within the requirements for tension-controlled behavior, even though the failure mode (concrete crushing or strand rupture) is generally considered to be nonductile.

Optimal Design

One goal in the design of a prestressed concrete member is to determine the number of stainless steel strands required to satisfy the requirements of the AASHTO LRFD specifications. For the purpose of this discussion, let us assume the design moment required by the AASHTO LRFD specifications that controls the design of a bridge is M_{reqd}, which is shown in Fig. 3 (left) as a dashed red line. The required design moment could be defined by the Strength I limit state, minimum reinforcement provisions, or the Service III limit state. The factored flexural resistance ϕM_n must be greater than or equal to M_{reqd}; therefore, any number of strands above the dashed red line satisfies the minimum requirements of the AASHTO LRFD specifications. For a factored flexural resistance ϕM_{n-rs} (shown as solid green circle in Fig. 3), which is slightly greater than M_{reqd}, the number of stainless steel strands is $A_{ps\text{-}rs}$. For this number of strands, the failure mode is rupture of strands. The corresponding ultimate curvature and ultimate deflection (that is the curvature and deflection, respectively, at failure) for $A_{ps\text{-}rs}$ are shown in Fig. 3 (middle) and Fig. 3 (left), respectively. By increasing the number of strands to $A_{ps\text{-}cc}$ as indicated by the solid blue square in Fig. 3, the failure mode changes from rupture of strand to crushing of concrete (Fig. 3 [middle]), while achieving the same ultimate deflection (Fig. 3 [right]).

Although designing for the crushing of concrete failure mode leads to greater flexural resistance of the girder, it does not result in the greatest ultimate deformation. Figure 3 shows that the greatest ultimate curvature and deflection (red triangle) is achieved when the girder fails due to simultaneous failure of concrete crushing in the compression zone and strand rupture in the tension zone. Depending on the value of the required moment M_{reqd}, increasing the number of strands only to achieve failure by crushing of concrete might not be necessary. Also, a different parametric study has shown that failure by concrete crushing may not be achievable for I-girders with a wide composite deck slab (large beam spacing).[1]

The region in Fig. 3 between the green circle and red triangle may be the desirable design area for bridge engineers, although designs in this zone lead to failure by rupture of strands. While strand rupture has not been seen as a desirable failure mode in the past, experimental results from the FDOT research project show that girders failing due to rupture of strands can still exhibit noticeable deformation and cracking before failure (Fig. 2), and can have significant reserve strength between the first flexural cracking and failure.[1] For optimal design in terms of deformability, area of stainless steel prestressing strand must be closer to $A_{ps\text{-}rs\text{-}cc}$ (the red triangle in Fig. 3).

Designing for Deformability

It is important that a structural member exhibit adequate deformation and cracking to give warning before failure. A common concern regarding the use of stainless steel strands is their low ultimate strain and the resulting limited expected deformation of the girder before failure.

There are two ways to increase the amount of deformation before failure of a girder prestressed with stainless steel strands that is anticipated to fail by rupture of strands.

- Increase the number of strands (reinforcement ratio). That results in an increase in concrete top-fiber strain ε_c, thereby increasing the curvature (Eq. [1]) and deflection at failure. This was demonstrated experimentally[4] and can also be seen in Fig. 3. For areas of stainless steel prestressing strand less than $A_{ps\text{-}rs\text{-}cs}$, increasing the number of strands results in an increase in ultimate deflection (Fig. 3 [right]). The question is, what would be the most appropriate target value for the concrete top-fiber strain when rupture of strand is the expected failure mode? For the greatest deformation, and therefore warning before strand rupture, the answer is the higher, the better: closer to 0.003 in./in.
- Decrease the initial tensioning stress in the strands (unless the design is controlled by the Service III limit state). The initial tensioning level affects the net tensile strain in the strands at failure. A greater net tensile strain (lower initial tensioning level) is desirable to achieve greater curvature at failure. Thus, ultimate curvature can be increased by increasing the net tensile strain as a result of reducing the initial tensioning stress (Eq. [1]).

This approach is contrary to the philosophy for designing with carbon steel strands, where the designer typically uses the maximum permitted initial tensioning level of the strand to satisfy concrete stress limits at the service limit state with the fewest strands. Engineers designing with stainless steel strands will need to have a deeper understanding of the material properties and be aware of strategies to deal with the consequences of the limited ultimate strain.

Conclusion

This article discusses the philosophy for designing precast concrete girders prestressed with stainless steel strands. Stainless steel strand has a much lower ultimate strain than conventional carbon steel strand, and this difference in material behavior has a significant effect on girder behavior. However, full-scale experimental tests have shown that precast concrete girders prestressed with stainless steel strands that fail due to rupture of strands may still have significant reserve strength from first flexural cracking to failure and exhibit noticeable cracking and deflection well before reaching their ultimate capacity. Therefore, it appears that precast concrete girders prestressed with stainless steel strands can be designed to satisfy all requirements of the AASHTO LRFD specifications, but they will likely fail due to rupture of strand. When the design of a precast concrete girder results in rupture of strand, the deformability of the girder may be increased by increasing the number of strands, up to a certain point. Furthermore, unless the design is controlled by the Service III limit state, the deformability can also be increased by decreasing the initial tensioning level. These issues are discussed in greater detail in the FDOT report.[1]

Work on this topic is ongoing as part of a research project for National Cooperative Highway Research Program Project 12-120, "Stainless Steel Strands for Prestressed Concrete Bridge Elements," which is to be completed in 2024. One goal of that project is to develop specifications for the design of prestressed concrete members using stainless steel strands. These specifications will be built on a broader understanding of requirements for ductility when using reinforcement materials with reduced ductility and will enable implementation of stainless steel strands at a national level.

References

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