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Effective Length of Cable-stayed Bridge Decks

Z. T. McNeil and F. M. Bartlett
Department of Civil and Environmental Engineering, Western University, London, Canada

Abstract: Cable-stayed bridge decks supported by transverse floorbeams are very slender concrete beam-columns that can be susceptible to buckling instability. The floorbeams partially restrain the ends of the deck against rotation and so reduce its effective buckling length. Equations to estimate the effective length are derived assuming the eccentricity of the floorbeam with respect to the deck slab further contributes to the torsional restraint provided by the floorbeams. The contribution of the eccentric slab increases the rotational restraint for steel floorbeams by at least 32% and the restraint of concrete floorbeams by more than 88%. Assuming a uniform applied bending moment causing single curvature, the effective length factor, k, of deck slabs restrained by steel floorbeams will likely exceed 0.90, while k for slabs restrained by concrete floorbeams is significantly lower, in the range of 0.6 to 0.85. Considering the eccentricity of the deck had a negligible influence on k of steel floorbeams and reduced k of concrete floorbeams by 8 to 11%. Therefore, neglecting the eccentricity of the deck slab significantly underestimates the rotational restraint provided by the floorbeams, but remains a reasonable approximation of the restraint for the purpose of determining the effective length factor, k.

1. Introduction

Cable-stayed bridge decks often consist of slender concrete deck slabs which must resist combined bending and axial loads. The span-to-thickness ratios for these elements can exceed 20 which, for simply supported ends, corresponds to slenderness ratios greater than 70. Figure 1a) shows the buckled shape of a slender deck slab spanning between steel transverse floorbeams. The deflection midspan between the floorbeams can cause significant second-order effects, which are approximately accounted for in the Canadian Highway Bridge Design Code (CSA, 2006) using a moment magnifier. The moment magnifier is a function of the critical buckling load of the slab, P_{cr}, computed as:

[1] $$P_{cr} = \frac{\pi^2 EI}{(kL)^2}$$

where EI is the flexural rigidity and kL is the effective buckling length of the deck slab, as shown in Figure 1b).

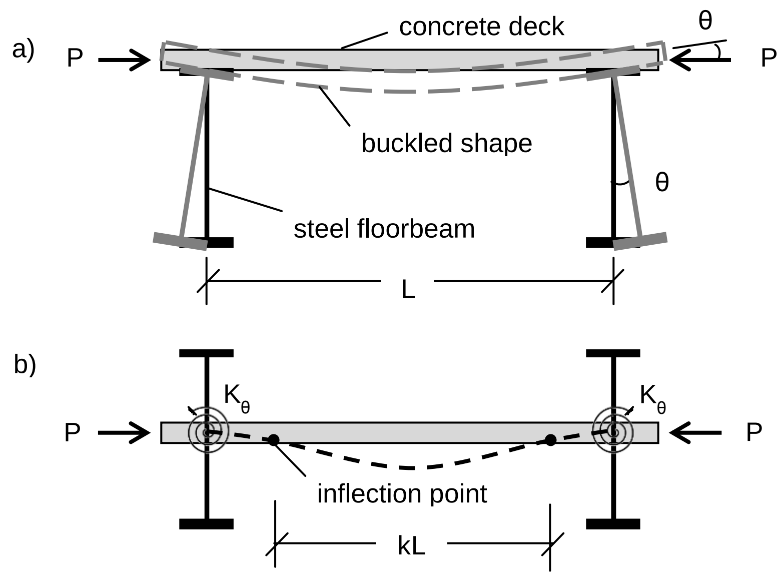

Figure 1: Deck slab instability: a) buckled shape; b) idealization with deck slab at the floorbeam centroid.

If the slab is pinned to the floorbeams, the ends will be free to rotate, the distance between the inflection points will equal the floorbeam spacing, L, and the effective length factor, k, will be 1.0. If the ends of the deck slab are restrained from rotation, the inflection points will move inwards and the effective length will approach a minimum value of half the floorbeam spacing (i.e., k = 0.5) if the ends are completely fixed.

Dimensionless ratios of relative stiffness, Ψ, are used to obtain the effective length factor, k, from an alignment chart (e.g., MacGregor and Bartlett, 2000) if the stiffnesses of the end restraints can be quantified. The assumption necessary for using these alignment charts is that all of the compression members buckle simultaneously. This assumption is more realistic for cable-stayed bridge decks than columns in buildings, since the compression force in these decks is almost constant between adjacent transverse floorbeams near the pylons.

Neglecting distortion, rotation at the ends of the deck slab must be accompanied by an equal rotation of the transverse floorbeams, as shown in Figure 1a). Therefore, the ends of the slab are partially restrained by the rotational restraint, K_θ, of the floorbeams. Assuming a uniform moment along the slab during the onset of buckling, the relative stiffness ratio is computed as:

[2] $$\Psi = \frac{2\sum(EI/L)}{K_\theta}$$

2. Idealization of the Rotational Restraint of Transverse Floorbeams

The rotational restraint of the floorbeams, K_θ, is the torque required to cause a unit rotation of the floorbeam. Assuming the floorbeams rotate about their centroid is analogous to assuming the deck slab is connected to the floorbeam centroid, as shown in Figure 1b). However, the deck slab is actually either shear connected to the top flange of steel floorbeams or cast monolithically with the web of concrete floorbeams. The significant axial stiffness of these slabs causes negligible deflection at the midpoint of the deck due to rotation of the floorbeams. The partial restraint of the eccentric deck slab is idealized in Figure 2 as a counteracting force, P, which causes the floorbeam centroid to deflect a distance, Δ, as the member rotates. Assuming the rotation, θ, is small, $\Delta \approx \theta(\bar{y} - h_s/2)$, where $\bar{y}$ is the distance from the top of the slab to the centroid and h_s is the thickness of the slab. The rotational restraint, K_θ, is therefore a function of the torsional rigidity, GC, the y-axis bending rigidity, EI_y, and the location of the centroid, $\bar{y}$.

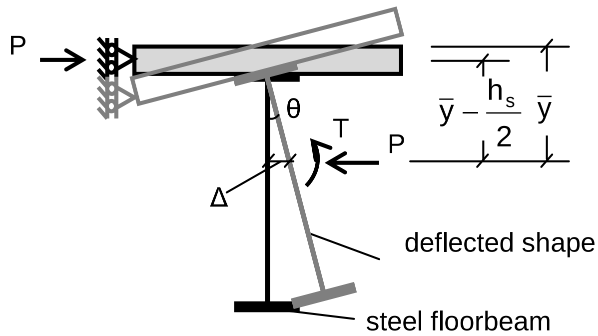

Figure 2: Horizontal deflection of floorbeam centroid.

3. Approximate Analytical Equations for the Rotational Restraint of Transverse Floorbeams

The rotational restraint, K_θ, of an elastic member with fixed ends rotating about its centroid due to an applied point torque is:

$$[3] \qquad K_\theta = \frac{T}{\theta} = \frac{GCs}{a(s-a)}$$

where θ is the rotation at the point of application of the point torque, T, at a distance, a, from the support. The shear modulus is G, C is the St. Venant torsional constant, and s is the length of the floorbeam.

If the eccentricity of the deck slab is considered, the force, P, shown in Figure 2, causes a restraining torque, T_e, equivalent to the product of P and the distance between the midpoint of the deck and the centroid of the floorbeam, $\bar{y} - h_s/2$. The deflection, Δ, caused by P can be obtained using the beam deflection equation for a fixed beam subjected to a point load. For small rotations, the rotational restraint provided by the eccentric deck slab, K_e, can be computed as (McNeil, 2013):

$$[4] \qquad K_e = \frac{T_e}{\theta} = \frac{3EI_y s^3 (\bar{y} - h_s/2)^2}{a^3 (s-a)^3}$$

Therefore, the total rotational restraint, K_θ, is sum of the restraint provided by the torsional stiffness of the floorbeam, Eq. 3, and that provided by the eccentric deck, Eq. 4:

$$[5] \qquad K_\theta = \frac{T}{\theta} = \frac{GCs}{a(s-a)} + \frac{3EI_y s^3 (\bar{y} - h_s/2)^2}{a^3 (s-a)^3}$$

Figure 3 shows a width of slab, w, spanning between transverse floorbeams. Using Eq. 5 to compute the rotational restraint of a floorbeam subjected to a point torque is analogous to assuming the width of the deck slab, w, is only 1m. This assumption yields small values for the relative stiffness, Ψ, from Eq. 2, since the entire floorbeam contributes to K_θ but only 1m width of deck contributes to the deck rigidity, EI. Since the effective length factor, k, reduces with Ψ, this yields very unconservative estimates of k and so Eq. 5 must be revised to account for more realistic loading conditions.

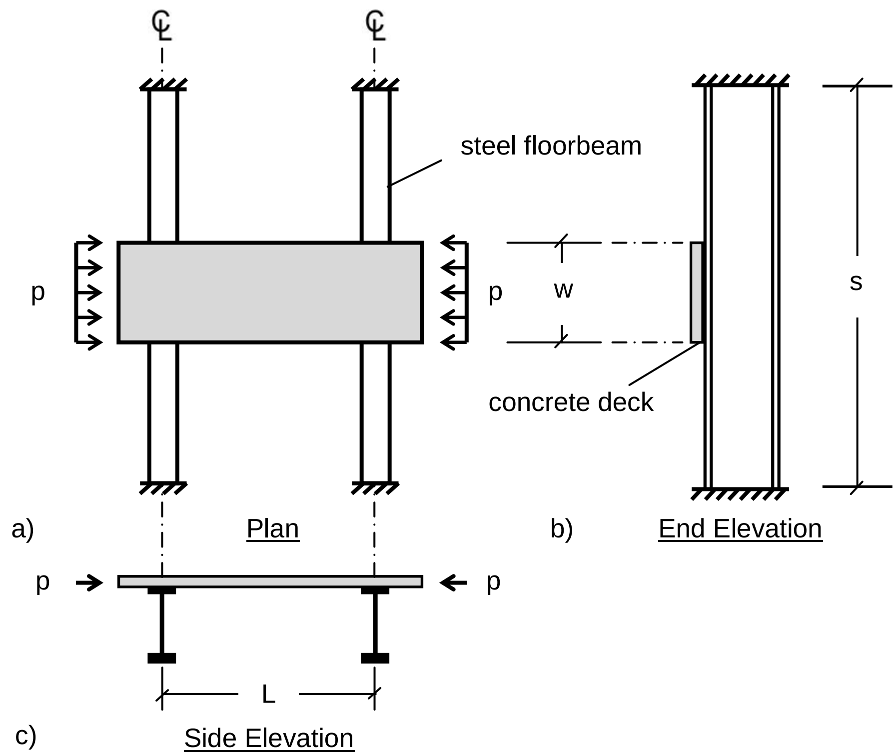

Figure 3: Concrete deck on steel floorbeams: a) plan; b) end elevation; and c) side elevation.

If a uniform torque is applied along a width, w, greater than 1m, the eccentricity of the deck slab can be idealized as a uniformly distributed restraint, p, as shown in Figure 3. For the purpose of this paper, it will be assumed that the uniform torque is applied from a width of slab equal to half the length of the floorbeam (i.e. w = s/2) and the slab is centered at the midspan of the floorbeams.

Eqs. 6 and 7, shown in Table 1, yield the rotational restraint at the quarter spans and midspan, respectively, of a floorbeam with fixed ends and a uniform torque applied between the quarter points. The rotational restraint, k_θ, is defined as the uniform torque that must be applied between the quarter points to cause a unit rotation, θ, at either the quarter spans (Eq. 6) or the midspan (Eq. 7).

Table 1: Rotational restraint of floorbeams with a uniform torque applied between quarter points.

Floorbeam End Restraints	**Rotational Restraint, k_θ**			
	Quarter span		**Midspan**	
Fixed against all translations and all rotations	[6]	$\frac{16GC}{s^2}+\frac{6144EI_y(\bar{y}-h_s/2)^2}{7s^4}$	[7]	$\frac{32GC}{3s^2}+\frac{6144EI_y(\bar{y}-h_s/2)^2}{13s^4}$
Fixed against all translations and torsional rotation	[8]	$\frac{16GC}{s^2}+\frac{768EI_y(\bar{y}-h_s/2)^2}{5s^4}$	[9]	$\frac{32GC}{3s^2}+\frac{6144EI_y(\bar{y}-h_s/2)^2}{57s^4}$

The derivations of Eqs. 6 and 7 are based on the assumption that the ends of the floorbeams are fixed against y-axis bending. This assumption is appropriate for bridges with concrete floorbeams, but bridges with steel floorbeams are more likely to behave as pinned. Accounting for this, the rotational restraint at the quarter span of a steel floorbeam is given by Eq. 8 in Table 1, and the restraint at midspan is given by Eq. 9.

The equations in Table 1 provide the uniform torque which must be applied to cause a unit rotation at either the quarter span or midspan of a floorbeam. The total rotational restraint, K_θ, can be obtained by multiplying the uniform restraint, k_θ, by the length of the uniform torque (i.e. $K_\theta = k_\theta(s/2)$).

4. Validation using SAP 2000

Eq. 5 was validated by performing a linear-elastic static analysis in SAP 2000 (Computers and Structures Inc., 2011). A solid steel bar 100mm in diameter, spanning 500mm between fixed supports was chosen so the contribution of the rotational restraint provided by the eccentric deck slab, K_e, would be a significant portion of the total restraint, K_θ. The bar was modelled as four frame elements 125mm long. To simulate the effect of the eccentric deck slab a rigid link, shown in Figure 4a), was used to connect the centroid of the frame element to a roller support at the top corner of the section. Figure 4b) demonstrates the effect of this support, forcing the centroid to deflect as the member rotates.

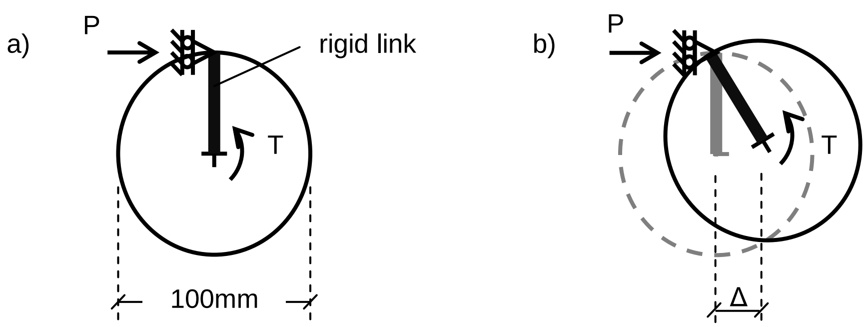

Figure 4: Model specimen: a) rigid link connecting the centroid to a roller; b) deflection of the centroid.

Eq. 5 was used to predict the rotation that would occur due to a point torque applied at both the midspan and quarter span of the member. Neglecting shear deformations, the SAP 2000 model predicted the exact same rotations as Eq. 5 for a 1kN·m torque applied at either location.

A similar linear-elastic static analysis was performed to validate Eqs. 6 and 7. The same section, spanning 500mm between fixed supports was idealized as one frame element from each support to the quarter points and 50 frame elements 5mm long between the quarter points. A uniform torque of 4kN·m/m was applied between the quarter points and rigid links and roller supports, shown in Figure 4, were placed every 5mm between the quarter points to simulate the eccentric deck slab.

Ignoring shear deformations, the model rotation at the quarter span was 7% less than predicted using Eq. 6 and the rotation at midspan was 1% less than predicted using Eq. 7. The derivations of Eqs. 6 and 7 assume the eccentric deck slab provides a uniformly distributed restraint, p, as shown in Figure 3. Figure 5 shows the reactions at the ends of the rigid links, which are not uniformly distributed. The links near the quarter points provide much higher restraining reactions than those near midspan, since the bending stiffness is much higher at the quarter points.

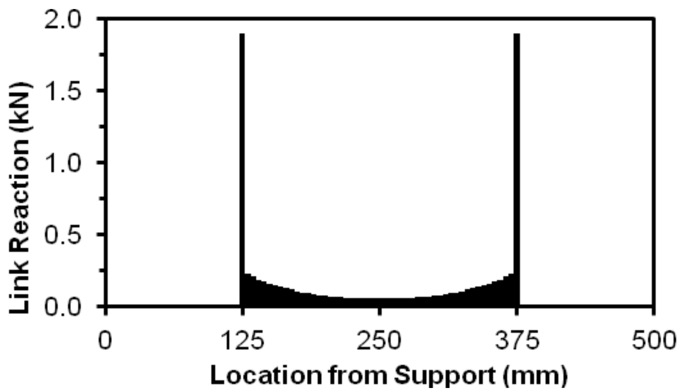

Figure 5: Reactions at link supports in SAP2000 model.

The model used to validate Eqs. 6 and 7 was modified to check Eqs. 8 and 9 by changing the supports from fixed against all rotations to fixed only against torsional rotations. This change causes the deflected shape to resemble that of a pin-ended member when bending about the y-axis, which is more representative of the behaviour of steel floorbeams. Ignoring shear deformations, the rotations at the quarter spans were 2% larger than predicted by Eq. 8 and midspan rotation was 1% lower than predicted by Eq. 9. The errors in the results obtained using Eqs. 8 and 9 can also be attributed to the assumption that the deck slab provides a uniformly distributed restraint, when the actual restraint is not uniform.

The assumptions made in deriving the equations in Table 1 may not accurately represent the true restraint of the deck slab, but provide a reasonable approximation for the purpose of estimating the rotational restraint of cable-stayed bridge floorbeams.

5. Case Studies - The Effective Length of Deck Slabs with Steel and Concrete Floorbeams

The steel plate girders in the Alex Fraser Bridge in Vancouver and the concrete T-beams in the Talmadge Memorial Bridge in Savannah, Georgia, were chosen as typical examples of transverse floorbeams in cable-stayed bridges. Figure 6a) shows the typical cross-section dimensions of the 28m long girders in the Alex Fraser Bridge, and Figure 6b) shows approximate dimensions of the 21.5m long T-beams in the Talmadge Bridge. The typical floorbeam spacing in these bridges varies significantly from 4.5m for the steel girders in the Alex Fraser Bridge to 8.61m for the concrete T-beams in the Talmadge Memorial Bridge.

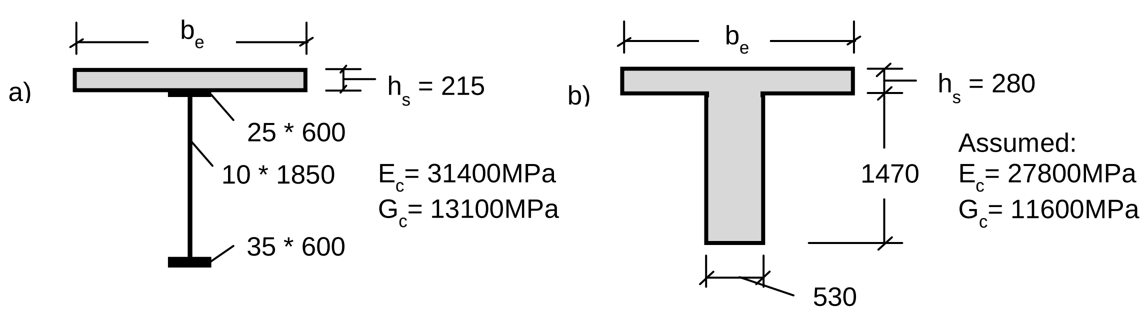

Figure 6: Typical floorbeam cross-sections: a) steel; b) concrete (dimensions in mm).

To determine the sectional properties of the steel and concrete floorbeams, an effective width of slab, b_e, that contributes to the rotational restraint of the floorbeams must be assumed. The effective width equation in Clause 5.8.2.1 of CSA S6-06 (CSA, 2006) was derived to account for shear lag in both composite beams and concrete T-beams subjected to strong-axis bending. Applied to the floorbeams in the Alex Fraser Bridge it indicates that the full width of slab is effective (i.e. b_e = 4.5m). Therefore, this equation is used as an upper bound for determining the sectional properties of floorbeams.

Since Clause 5.8.2.1 was not derived for determining the torsional constant, C, it may be unconservative to assume the full width of deck is effective at restraining rotation. As a lower bound for steel floorbeams it will be assumed that only half of the available deck slab effectively resists rotation.

The provisions in Clause 13.8.2.7 of CSA A23.3-04 (CSA, 2004) are for determining the effective slab width for computing the torsional constant, C, of beams in two-way slab systems. These provisions are assumed to provide a lower bound for calculating the sectional properties of concrete floorbeams.

Hsu (1968) subjected a member with moderate torsional reinforcement to pure torsion to study the effect of torsional cracking. Immediately after cracking it was observed that the torsional stiffness, CG, was reduced to 20% of the uncracked value. To provide a lower bound for determining the sectional properties, the portion of the torsional constant, C, corresponding to concrete will be taken as 20% of the uncracked value.

Table 2 shows the upper and lower bound cross-sectional properties of the floorbeams investigated, where UB_S and LB_S are the upper and lower bound values for steel floorbeams and UB_C and LB_C are the bounds for concrete floorbeams. The upper bound values are computed assuming the maximum width of slab, from Cl. 5.8.2.1 of CSA S6-06 (CSA, 2006), is effective at resisting rotation and the concrete is uncracked in torsion. The lower bound properties for steel floorbeams were computed assuming half of the available deck slab effectively resists rotation and the deck slab is cracked in torsion. The lower bound properties for the concrete floorbeams were computed using CSA A23.3-04 (CSA, 2004) to determine the effective slab width, and assume the concrete is cracked in torsion.

Table 2: Upper and lower bound cross-sectional properties of steel and concrete floorbeams.

Property	**Steel (Alex Fraser)**		**Concrete (Talmadge)**		**UB_C / UB_S**	**LB_C / LB_S**
	UB_S	**LB_S**	**UB_C**	**LB_C**		
b_e (m)	4.50	2.25	6.44	2.77	1.43	1.23
EI_x ($*10^6$ kN·m^2)	18.3	15.9	15.8	12.3	0.87	0.77
EI_y ($*10^6$ kN·m^2)	51.5	6.62	174	14.3	3.38	2.16
GC ($*10^4$ kN·m^2)	19.0	1.93	129	19.5	6.76	10.1

The x-axis bending rigidity, EI_x, of concrete floorbeams is 13 to 23% smaller than that of steel floorbeams, while the y-axis bending rigidity, EI_y, is 2.2 to 3.4 times larger than that of steel floorbeams. The difference in y-axis bending rigidity can be expected since the deck slab is 30% thicker and the effective slab width is from 23 to 43% larger in the Talmadge Memorial Bridge than in the Alex Fraser Bridge. However, the torsional rigidity, GC, of the concrete floorbeams exceeds that of the steel floorbeams by a factor of 6.8 to 10. This difference is not only due to the differences in the deck slab dimensions, but is largely due to T-sections being much more efficient at resisting St. Venant torsion than plate girders.

Table 3 shows the upper and lower bound rotational restraints, which were computed using Eqs. 6 and 7 for concrete floorbeams and Eqs. 8 and 9 for steel floorbeams. Table 3 also shows the increase in rotational restraint obtained by accounting for the eccentricity of the deck slab. The contribution of the rotational restraint that is due to the eccentric deck slab, K_e, corresponds to the second term in Eqs. 6 to 9. The contribution of the eccentric deck slab is significant for the bridge with steel floorbeams, representing a minimum of 24% of the total rotational restraint, K_θ. The contribution is greater for the bridge with the concrete floorbeams, representing at least 47% of K_θ.

Table 3: Rotational restraint bounds for bridges with steel and concrete floorbeams.

	Steel (Alex Fraser)		**Concrete (Talmadge)**	
	K_θ ($*10^4$ kN·m/rad.)	K_e/K_θ	K_θ ($*10^4$ kN·m/rad.)	K_e/K_θ
Upper bound at midspan	4.81	0.25	60.7	0.47
Lower bound at midspan	0.75	0.51	11.4	0.57
Upper bound at quarter span	7.13	0.24	101	0.53
Lower bound at quarter span	1.10	0.50	19.4	0.63

The results in Table 3 were used in Eq. 2 to determine the relative stiffness ratio, Ψ, and a range of effective length factors, k, were obtained using an alignment chart (e.g., MacGregor and Bartlett, 2000). Figure 7 shows the approximate ranges of effective length factors for concrete cable-stayed bridge decks with steel or concrete transverse floorbeams. The vertical axis shows the effective length factor, k, of the deck slab, which ranges from 0.5 to 1.0. An effective length factor, k, of 0.5 corresponds to a deck slab spanning between floorbeams with infinite rotational restraint (fixed), while k =1.0 corresponds to a slab spanning between floorbeams with no rotational restraint (pinned).

The lines for steel floorbeams in Figure 7 are linear since they connect only two data points, one at the quarter span computed using Eq. 8 and one at midspan computed using Eq. 9. The lines for concrete floorbeams are not linear since they connect several data points from the quarter span to midspan, which were all computed using equations that were derived using the same methodology as Eqs. 6 and 7 in Table 1.

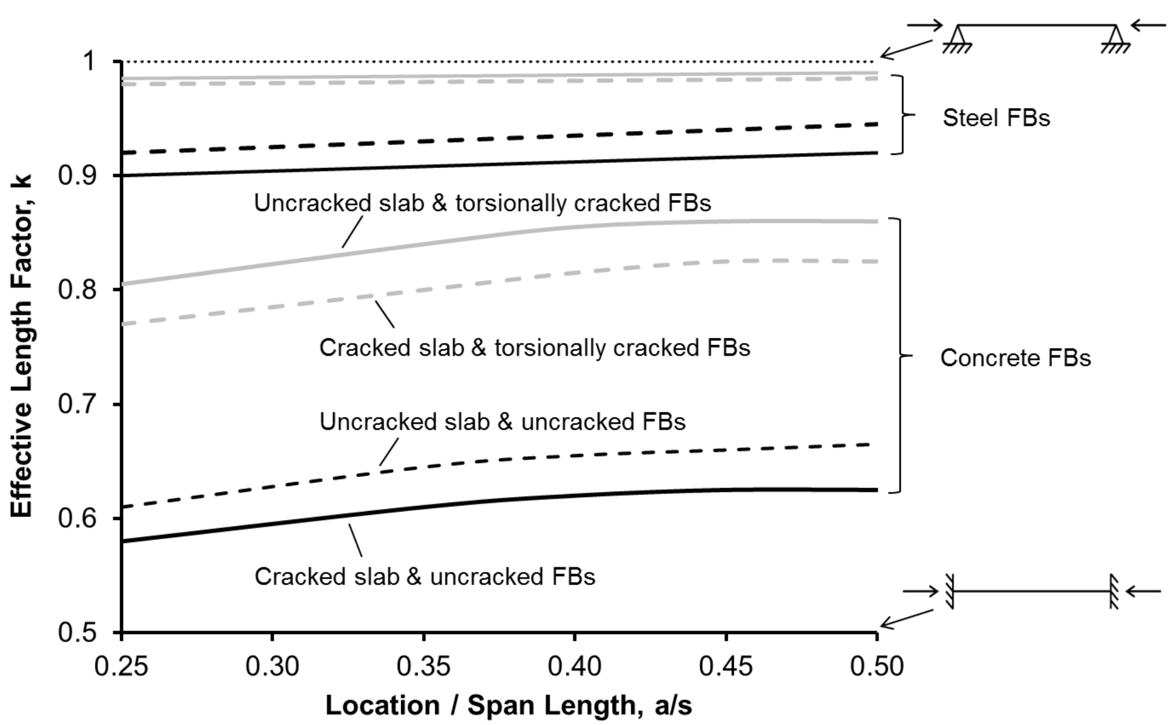

Figure 7: Effective length factors for cable-stayed bridge decks.

The lower bound estimates of the effective length factor, shown by the black lines in Figure 7, were obtained using the upper bound rotational restraints from Table 3, which were computed assuming the floorbeams remain uncracked in torsion. The grey lines correspond to the upper bound estimates of k and were obtained assuming the concrete portions of the floorbeams crack in torsion. The solid black lines provide the lowest estimates of k by considering the concrete portions of the floorbeams uncracked in torsion and the flexural rigidity, EI, of the deck slab in Eq. 2 is taken as 70% of the uncracked rigidity, E_cI_g, as suggested by CSA A23.3-04 (CSA, 2004) to account for non-linear responses in columns. The solid grey lines provide overly conservative estimates of k, considering the concrete portion of the floorbeams to be cracked in torsion but the deck slab to remain uncracked in flexure. A more practical range of k is bound between the grey and black dashed lines, which were computed assuming that the deck slab is only cracked in flexure when the floorbeams are cracked in torsion.

The lowest value of k for concrete deck slabs supported by steel floorbeams is 0.90 at the quarter span when the entire uncracked concrete slab is assumed effective at resisting rotation but cracks in flexure. These assumptions are likely unconservative, so it seems likely that steel floorbeams are incapable of reducing the effective length factor below 0.90. The more practical range of k for concrete decks on steel floorbeams ranges from a minimum of 0.92 at the quarter span to a maximum of 0.98 at midspan.

The lowest k value for concrete deck slabs supported by concrete floorbeams is 0.58 at the quarter span and corresponds to a 6.44m width of deck that is assumed effective at resisting rotation, the floorbeams remain uncracked in torsion, and the slab cracks in flexure. The highest k value is 0.86 at midspan assuming only 2.77m of slab effectively resists rotation and the floorbeams crack in torsion, but the slab remains uncracked in flexure. However, common practice, as for the Talmadge Memorial Bridge, is to post-tension concrete floorbeams, making it unlikely that they will crack in torsion. Therefore, the grey lines are over-conservative suggesting that the rotational restraint provided by concrete floorbeams can reduce the slab effective length factor well below 0.9. The more practical range of k, neglecting torsional cracking, is from 0.61 at the quarter span to 0.75 at midspan.

The flexural stiffness, EI/L, is significantly smaller for the slab on concrete floorbeams since the floorbeam spacing, L, is larger. The concrete floorbeams are also significantly shorter than the steel floorbeams, so the rotational restraint, K_θ, should be higher. The relative stiffness ratio, Ψ, and effective length factor, k, will therefore be smaller for slabs supported by concrete floorbeams, since the EI/L term in Eq. 2 is smaller and K_θ is larger. If the concrete floorbeam spacing is reduced to 4.5m and the length is increased to 28m, the EI/L term will be almost twice as large for the slab on concrete floorbeams as that on steel floorbeams, and any difference in k values will reflect the increased rotational restraint of concrete floorbeams. For these dimensions, the bounds of k range from 0.77 at the quarter span to 0.95 at midspan, and the more likely values of k, neglecting torsional cracking, are all less than 0.89. Changing the dimensions of the bridge with concrete floorbeams significantly increased the range of effective length factors, but if torsional cracking is neglected the minimum rotational restraint of the concrete floorbeam is still 3 times larger than the highest possible restraint of steel floorbeams.

The eccentricity of the deck slab increases the rotational restraint of floorbeams significantly, but does not have a large influence on the effective length factor, k. If the eccentricity of the slab is ignored the k values for slabs supported by steel floorbeams would range from 0.92 to 0.99 instead of 0.90 to 0.99. For slabs supported by concrete floorbeams k would range from 0.65 to 0.93 if the eccentricity of the deck slab is neglected, rather than 0.58 to 0.86 if the eccentricity is considered. Therefore, neglecting the eccentricity of the slab reduces the rotational restraint provided by concrete floorbeams by a factor of 1.9, but only increases the effective length factor by 12%. The small influence is due to the relationship between k and the relative stiffness, Ψ, on the alignment chart. The relative stiffness can range from 0 for fixed end supports to infinity for a pinned supports, while the effective length factor only ranges from 0.5 to 1.0 for the same support conditions. Since Ψ has an infinite range and k only has a range of 0.5, a significant increase in Ψ must relate to a much smaller increase in k.

6. Summary and Conclusions

Floorbeams supporting slender concrete cable-stayed bridge decks, that are subjected to axial compression and bending, provide both vertical and rotational restraints. The effectiveness of the rotational restraint of floorbeams is not only a function of the torsional rigidity, GC, but also the weak-axis bending rigidity, EI_y, and the location of the floorbeam centroid, $\bar{y}$.

Idealizing the restraint of an eccentric deck slab as a uniformly distributed force provides a reasonable approximation of the rotational restraint of floorbeams for the purpose of determining the effective length factor, k.

The eccentricity of the deck slab contributes significantly to the rotational restraint provided by the floorbeams, representing at least 24% and 47% of the total rotational restraint provided by representative steel and concrete floorbeams, respectively.

The effective length factor, k, approaches 1.0 for deck slabs supported by steel floorbeams and is significantly less than 0.90 for slabs supported by concrete floorbeams, typically ranging from 0.6 to 0.85 for realistic cases.

The eccentricity of the deck slab has a negligible influence on k for decks supported by steel floorbeams, and only slightly influences k of decks supported by concrete floorbeams. While the eccentricity of the slab doubled the rotational restraint of concrete floorbeams it only decreased k by a maximum of 11%. Therefore, neglecting the eccentricity of the deck slabs provides a reasonable approximation of the rotational restraint of floorbeams, for the purpose of obtaining the effective length factor, k, of cable-stayed bridge decks.

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