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Interface friction in the service load assessment of slab-on-girder bridge beams

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Abstract. Many slab-on-girder bridges around the world are being assessed because they are approaching the end of their anticipated design lives or codes are permitting higher allowable loads. Current analytical techniques assume that the concrete and steel components act independently, typically requiring full-scale load testing to more accurately predict the remaining strength or endurance of the structure. However, many of the load tests carried out on these types of bridges would be unnecessary if the degree of interaction resulting from friction at the steel-concrete interface could be adequately modeled. Experimental testing confirmed that interface friction has a negligible effect on the flexural capacity of a slab-on-girder beam however, it also showed that interface friction is significant under serviceability loading. This has led to the development of an improved analytical technique which is presented in this paper and referred to as the slab-on-girder mixed analysis service load assessment approach.

Key words: mixed analysis; service load assessment; partial-interaction; non-composite; interface friction; slab-on-girder beams.

1. Introduction

Non-composite slab-on-girder bridges have no mechanical shear connection at the steel-concrete interface. Therefore, at the time of their design, calculations of their flexural capacity assumed that the steel and concrete components acted independently. The strength of the section may have also been taken as the strength of the steel girders alone. The possibility of interaction between the two components was ignored and this allowed for a simple and conservative design approach. Due to recent increases in load limits and the reality that many slab-on-girder bridges are approaching the end of their anticipated design lives, evaluation of these bridges is becoming increasingly common.

Currently, no analytical technique has been developed that can allow for interaction between the steel and concrete components in slab-on-girder beams. Hence, full-scale load testing of bridges is employed to more accurately assess the behaviour of existing bridges, which is an expensive exercise as it requires significant instrumentation and is labour intensive and furthermore, is disruptive to traffic flow. Even once a full-scale test has been performed, and a degree of composite action identified, there is not

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yet any precise way of dealing with the information since the characteristics of unintentional composite action have not been thoroughly investigated (Roberts *et al.* 1997). Nowak and Tharmabala (1998) and Burdette and Goodpasture (1988) recommended that efforts should be made to improve analytical methods that account for the increase in strength of slab-on-girder bridges due to unintentional composite action.

Full-scale bridge testing has consistently shown that there is a large amount of reserve strength in existing slab-on-girder bridges (Roberts *et al*. 1997, Nowak and Tharmabala 1998). Research by Nowak and Tharmabala (1998) identified that this reserve strength is due to: oversimplified structural analysis techniques; load distribution between girders; the stiffening effect of parapet walls and railings if acting integrally with the concrete deck; unintended continuity resulting from the concrete deck cast continuously over the simply supported steel girders in multi-span bridges; inaccurate material properties, which is easily corrected by testing samples obtained from the structure; and finally, unintended interaction between the steel and concrete components.

It was found that there is significant overestimation of load effects by using approximate and simplified structural analysis techniques. One such simplified analysis method is the American Association of State Highway and Transportation Officials (AASHTO) method that uses a rating system for non-composite bridges based on the flexural capacity of the steel girders alone (Stallings and Yoo 1993). Such a general approach is inadequate in dealing with the complex nature of unintentional composite action. Furthermore, Burdette and Goodpasture (1988) identified unintentional composite action as one of the primary reasons for the large reserve strength of slab-on-girder bridges and it was concluded that the unintentional composite action is a result of chemical bonding and friction at the steel-concrete interface. In addition, it was found that the chemical bond was unreliable due to its sensitivity to bridge loadings (Burdette and Goodpasture 1988). Hence, it can be assumed that the chemical bond is broken early in the life of slab-on-girder bridges and therefore will have little effect on its behaviour under service load and need not be considered.

By developing a more rigorous analysis technique that allows for unintended composite action due to interface friction, this paper addresses two of the important items responsible for the reserve strength of slab-on-girder bridge beams. Although frictional effects may be small from the original design point of view, in some cases slab-on-girder bridges are only marginal with respect to structural adequacy and would only need a small increase in theoretical capacity to permit their continued use (Roberts *et al.* 1997). Full-scale bridge testing indicates that unintentional composite action has significant influence under serviceability loads (Burdette and Goodpasture 1971) but little effect on the ultimate capacity of the bridge (Bakht and Jaeger 1992).

In order to verify these results, an experimental study was conducted to examine the behaviour of slab-on-girder beams under loading at serviceability levels and at ultimate. It is not the aim of this paper to provide detailed results of the experimental tests as this is covered adequately elsewhere (Seracino and Hocking 2001). Hence, details of the beams are only summarised to provide the necessary background and only results specific to validating the model developed in this paper are presented.

The following section qualitatively defines where the typical strain distribution in a slab-on-girder beam lies with respect to the range of possible distributions under serviceability loads, which is required to provide a suitable background for the model presented in this paper. This is then followed by a brief summary of the experimental tests undertaken on four slab-on-girder beams that are used to validate the model. Finally, the improved analysis technique is presented allowing for unintended composite action in slab-on-girder beams due to interfacial friction in the service load assessment of existing structures.

2. Strain distributions

Fig. 1 illustrates typical strain distributions for a steel-concrete beam subject to flexure depending on the degree of interaction. It is assumed that the materials remain linear-elastic under fatigue loading hence the stress distribution is directly proportional to the strain distribution. The no-interaction strain distribution occurs when there is no shear connection and the steel and concrete components act independently and hence, there are two neutral axes at the centroids of the steel and concrete components (Seracino *et al.* 2001). This is the type of analysis currently used in the assessment of slab-on-girder beams. A situation of full-interaction arises when there is no slip at the interface and hence, there is a single continuous strain distribution for the entire section with only one neutral axis at the centroid of the composite section. This analysis is common in the design of new composite steel-concrete structures because of its simplicity and conservativeness with respect to the magnitude of the shear force resisted by the stud shear connectors. Consequently, these two distributions define the range of possible distributions so that for a steel-concrete beam with an intermediate degree of interaction, or partial-interaction, the strain distribution must lie within these bounds.

The slip-strain, *ds/dx*, at the steel-concrete interface is a measure of the degree of interaction between the components. In Fig. 1, the slip-strain is identified as the difference between the strain in the concrete element and the strain in the steel element at the interface that is, $(\varepsilon_c)_{bot} - (\varepsilon_s)_{top}$. The maximum slip-strain possible is that determined from a no-interaction analysis.

The presence of frictional forces at the interface of a slab-on-girder beam provides the mechanism for partial-interaction between the steel and concrete components, therefore the stresses for a given applied bending moment will be less than those predicted by no-interaction theory. As the degree of interaction due to interfacial friction alone is relatively small, the partial-interaction distribution will tend towards that of the no-interaction bound as illustrated by the dashed line in Fig. 1.

The behaviour exhibited by slab-on-girder beams due to the effect of friction at the steel-concrete interface can be examined as a special case of classical linear-elastic partial-interaction theory developed by Newmark *et al.* (1951). Furthermore, much of the work done to investigate the partial-

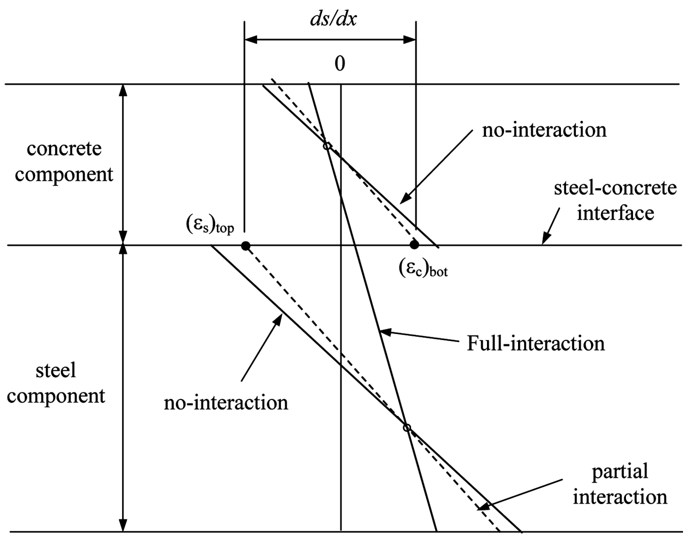

Fig. 1 Steel-concrete beam strain distributions

interaction behaviour of composite beams by Seracino *et al*. (2002) and Oehlers and Sved (1995) proved to be invaluable in this investigation of slab-on-girder beams.

3. Experimental testing

Researchers (Nowak and Tharmabala 1998, Bakht and Jaeger 1990) have recommended that analytical methods developed to estimate the reserve strength of non-composite bridges should be based on the results of full-scale bridge testing. However, it is difficult to separate the unintentional composite behaviour from the other factors that increase the reserve strength of slab-on-girder bridges in the data obtained from full-scale bridge tests. The effect of friction in unintentional composite action, which is the focus of this paper, is more easily examined by isolating a single slab-on-girder beam.

A series of four beam tests were undertaken to validate the approach developed in this paper. The cross-section of the 5 m long simply supported beams tested is shown in Fig. 2. The top surface of the steel beams was prepared in two different ways prior to casting of the concrete slab. The surface of the top flange of two of the beams (referred to as the T-series) was coated with a thin film of grease and covered with a Teflon sheet prior to casting the concrete so that the frictional resistance along the interface will be minimised to simulate the no-interaction bound. The remaining two beams (referred to as the N-series) received no special surface treatment to represent the actual conditions during construction.

Single concentrated loads were applied to the top of the beam and were moved to five positions along the length to simulate a moving load. Steel weights were also distributed along the length of one of the N-series beams to investigate the effect of increased dead load on the response. Steel and concrete strains, deflection, horizontal slip and vertical separation were continuously recorded at each load location along the beam.

Crucial to this research, comparison of the results between the N- and T-series beams and no-interaction theory confirmed that composite action due to interface friction alone was present in the test beams. At the conclusion of the tests under serviceability loads, the beams were tested to failure to quantify the effect of interface friction on the flexural capacity. The following section discusses the results of the ultimate load tests, which were found to be much less significant. The results of the serviceability tests are presented later to validate the new service load assessment technique developed.

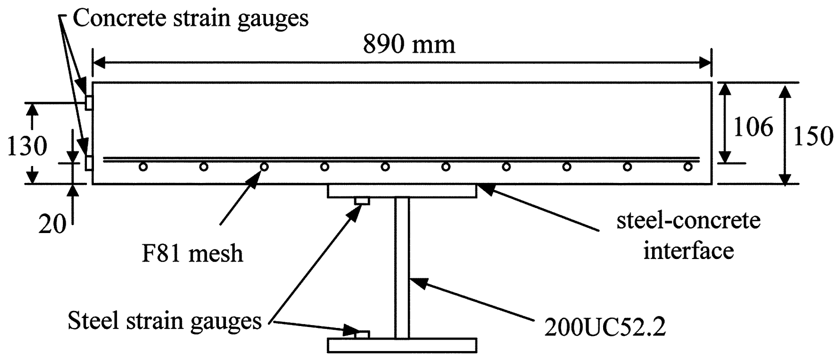

Fig. 2 Cross section of the experimental slab-on-girder beam

4. Flexural capacity

As referred to in the introduction, full-scale load tests indicate that unintentional composite action does not contribute to the flexural capacity of slab-on-girder beams. This observation was confirmed experimentally with only a 2% difference in the moment capacity between the N- and T-series beams. This insignificant increase can be further confirmed by performing a standard rigid-plastic analysis including the degree of shear connection resulting from the uniform frictional resistance along the interface. The analysis is simplified by ignoring the local increases in frictional resistance under the concentrated loading points hence, only the concrete dead load is considered. This conclusion was of course expected as the frictional resistance is much smaller than the stress resultants at failure. As a result, an engineer undertaking an assessment of a slab-on-girder bridge should not consider any gain in flexural capacity due to unintentional composite action alone. The remainder of this paper is devoted to the development of a suitable analysis technique to quantify the effect of unintentional composite action in the service load assessment of slab-on-girder bridges.

5. Service load behaviour

When initial comparisons were made to theoretical no-interaction strains using uncracked concrete sectional properties, it was observed that the experimental strains were typically larger which physically cannot be possible. The reason for this error was that even under low serviceability loads, some cracking of the concrete occurs reducing the effective flexural rigidity of the cross section. This highlights the importance of using realistic material and sectional properties in theoretical calculations that represent existing conditions in the field. Moses *et al*. (1989) also recommended the use of site-specific data to improve predictions of the remaining life of existing bridges.

In developing the analytical procedure to quantify the effect of interface friction on the response of slab-on-girder beams, a model developed for composite beams with limited-slip-capacity shear connectors by Oehlers and Sved (1995) was of particular interest. The limited-slip-capacity approach is referred to as a mixed analysis because it models the rigid-plastic behaviour of the shear connectors, while the steel and concrete components remain linear elastic. This technique has been modified to suit the behaviour of slab-on-girder beams subjected to serviceability load levels where the steel and concrete components behave elastically while the frictional capacity at the interface is achieved. The modification involved replacing the total strength of the shear connectors in the shear span P_{sh} with the frictional resistance of the shear span F_{fric} given by the following relationship

$$F_{fric} = MIN\begin{cases} \mu V_L \\ \mu V_R \end{cases} \tag{1}$$

where V_L and V_R are the vertical shear forces in the left and right shear span respectively as shown in Fig. 3, and μ is the coefficient of friction between the concrete and steel at the interface. Experimental testing (Singleton 1985) has shown that μ oscillates between 0.7–0.95 for a steel and concrete interface when subjected to cyclic loading. Singleton suggested that μ starts at 0.95 and gradually reduces to 0.7 with increasing number of cycles as the contact surfaces become polished. Perhaps unexpectedly, it was observed that μ subsequently increases to 0.95 as unpolished aggregates become exposed increasing the roughness of the interface. This oscillation of μ continues as the interface cycles between polished

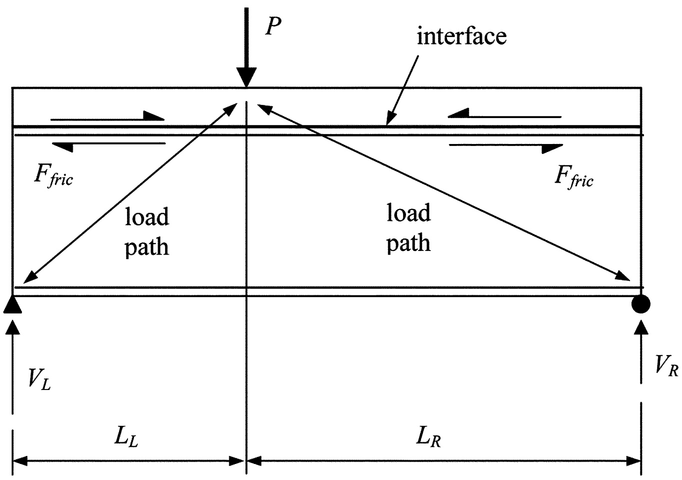

Fig. 3 Frictional resistance along the steel-concrete interface

and roughened states. Hence, it is recommended to use 0.7 in an assessment, which will provide a conservative estimate of the remaining endurance.

As the mixed analysis approach only requires the magnitude of the force along the interface (Oehlers and Sved 1995), the non-linear distribution of the frictional flow force along the interface, with local peaks near supports and externally applied loads (Oehlers *et al*. 2000), is of no concern. It is also assumed that the frictional resistance F_{fric} is constant regardless of the slip, which is consistent with the rigid-plastic assumption used for the shear connectors in the original application of the mixed analysis approach.

For the example illustrated in Fig. 3, $V_R < V_L$ and so, the right shear span will govern the analysis as the frictional resistance there will be less. This is in contrast to a composite beam with stud shear connectors because in this example, the frictional resistance in the left shear span would govern as friction must first be overcome before there is slip along the interface and the connectors begin resisting load.

The stress resultants acting at an analysis section (that is, the position of maximum moment) allowing for interface friction in a slab-on-girder beam is shown in Fig. 4 where the axial forces in the components are acting through the respective centroids.

Eqs. (2) to (4) define the mathematical model for predicting the slip-strain due to the effects of interface friction in slab-on-girder beams, which have been modified appropriately from that originally presented by Oehlers and Sved (1995). Eq. (2) assumes that the steel and concrete components have the same curvature ϕ_{fric}, and hence there is no separation at the steel-concrete interface, which is reasonable based on the experimental testing that was performed (Seracino and Hocking 2001). Small separation was recorded between flexural cracks in the concrete away from the applied load where the curvature in the uncracked concrete blocks was less than that of the steel section below. However, no measurable separation was observed in the vicinity of the load.

$$\frac{M_c}{(EI_{eff})_c} = \frac{M_s}{(EI)_s} = \phi_{fric} \tag{2}$$

where M_c and M_s is the moment in the concrete slab and steel beam respectively, $(EI)_s$ is the flexural

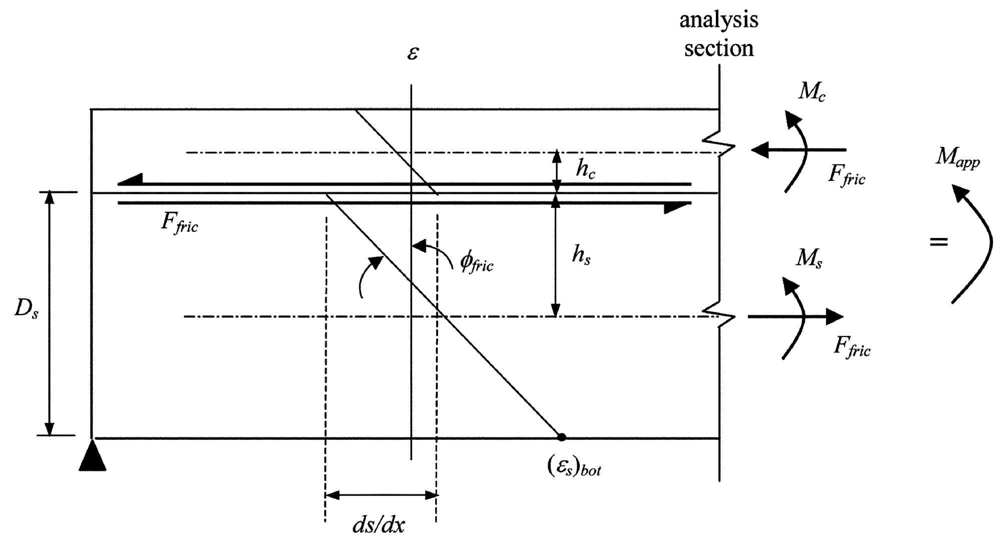

Fig. 4 Stress resultants in a slab-on-girder beam

rigidity of the steel beam, and $(EI_{eff})_c$ is the flexural rigidity of the concrete slab. An effective moment of inertia for the concrete slab I_{eff} is used to allow for the effect of concrete cracking.

The total applied moment M_{app} is resisted by three components given by the following equilibrium equation

$$M_{app} = M_s + M_c + F_{fric}(h_s + h_c) \tag{3}$$

where h_c and h_s is the distance between the steel-concrete interface and the centroid of the concrete slab and steel beam respectively. The last term in the right hand side of Eq. (3) is referred to as the composite moment $M_{comp} = F_{fric}(h_s + h_c)$ because it is a result of the composite action between the concrete and steel components.

The slip-strain at the steel-concrete interface can be calculated from the following

$$\frac{ds}{dx} = \left(h_c\phi_{fric} - \frac{F_{fric}}{(EA)_c}\right) - \left(-h_s\phi_{fric} + \frac{F_{fric}}{(EA)_s}\right) \tag{4}$$

where $(EA)_c$ and $(EA)_s$ is the axial rigidity of the concrete slab and steel beam respectively.

The following section describes the procedure for applying this mixed analysis technique to the assessment of slab-on-girder beams.

5.1. Slab-on-girder mixed analysis service load assessment approach

In an assessment, one of the major concerns of the engineer is the maximum tensile stress range in the steel beam, which can be determined once the strain at the bottom of the steel beam $(\varepsilon_s)_{bot}$ is known. Currently, the most sophisticated hand procedure available to the engineer is a no-interaction analysis where the moment contribution of the concrete slab to the resistance of the section is considered, probably assuming that the concrete section is fully cracked. However, with this new application of the traditional mixed analysis approach, a more accurate and realistic assessment of the stress profile can be obtained allowing for composite action due to interface friction in slab-on-girder beams.

From Fig. 4, the bottom tensile strain in the steel beam is given by

$$(\varepsilon_s)_{bot} = \frac{F_{fric}}{(EA)_s} + \frac{(D_s - h_s)M_s}{(EI)_s} \quad (5)$$

where D_s is the total depth of the steel beam. By substituting Eq. (2) into Eq. (3) for M_c, the following expression for the moment in the steel beam is obtained

$$M_s = \frac{M_{app} - M_{comp}}{1 + \dfrac{(EI_{eff})_c}{(EI)_s}} \quad (6)$$

Finally, substituting Eq. (6) into Eq. (5) and upon simplification, gives the following expression for the bottom tensile steel strain

$$(\varepsilon_s)_{bot} = \frac{F_{fric}}{(EA)_s} + \frac{(D_s - h_s)(M_{app} - M_{comp})}{\sum EI} \quad (7)$$

where $\Sigma EI = (EI_{eff})_c + (EI)_s$.

A conservative assumption would simply be to use the elastic fully cracked moment of inertia for the concrete slab I_{cr}. However, it will be shown that the following simple model (Standards Australia 1994) for rectangular reinforced concrete sections results in conservative, but significantly more accurate results

$$I_{eff} = \begin{cases} (0.02 + 2.5p)bd^3 & \text{when } p \geq 0.005 \\ (0.1 + 13.5p)bd^3 \leq 0.06bd^3 & \text{when } p < 0.005 \end{cases} \quad (8)$$

where p is the reinforcement ratio given by

$$p = \frac{A_{st}}{bd} \quad (9)$$

where A_{st} is the cross sectional area of tension reinforcement, b is the effective width of the concrete slab and d is the effective depth.

Once $(\varepsilon_s)_{bot}$, ϕ_{fric} and ds/dx are defined using Eqs. (7), (2) and (4) respectively, the stress profile can be determined for the cross section allowing for the composite action from interface friction. The following section validates and illustrates the use of this approach using the results of the experimental tests.

5.2. Validation against experimental data

The slab-on-girder mixed analysis service load assessment approach to predict the maximum tensile strain in the steel beam described in the previous section is validated by comparing with experimental data (Seracino and Hocking 2001). For reference, the results of other analysis approaches are also provided.

The dashed line in Fig. 5 is the maximum experimental bottom tensile steel strains for a range of applied moments taken at the midspan. Note that for the maximum M_{app} shown in Fig. 5, the maximum steel stress for the section tested (see Fig. 2) was approximately half the yield stress, which can be considered a maximum allowable serviceability stress.

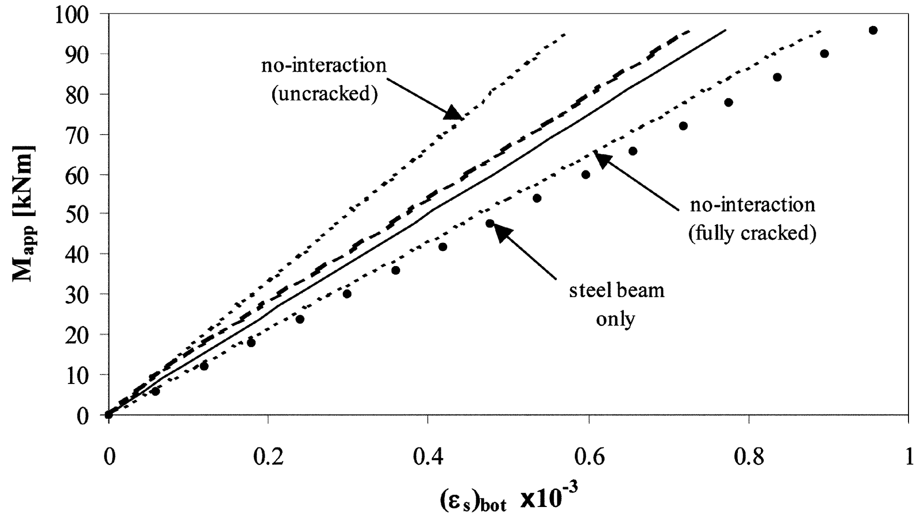

Fig. 5 Variation of bottom tensile steel strain

Also shown in Fig. 5 is an unsafe lower bound to the bottom steel strain that was obtained from a no-interaction analysis assuming the concrete is uncracked. It can be seen that the experimental results follow this bound until an applied moment of approximately 15 kNm is reached at which point the moment in the slab reaches the cracking moment and there is a softening of the response. The safe upper bound is also plotted in Fig. 5, which was also obtained from a no-interaction analysis however, the flexural rigidity of the slab was based on the elastic fully cracked section. Using this safe upper bound results in an overly conservative assessment. For comparison, the dots in Fig. 5 represent the bottom tensile steel strain assuming that the steel beam alone resists the applied loading, which is how the steel beams in existing structures may have been designed. Hence, the effect of composite action due to interface friction alone is clear as it significantly reduces the steel tensile strains and ultimately, increases the remaining strength or endurance of the structure. Finally, the solid line in Fig. 5 is the predicted bottom tensile steel strain from the slab-on-girder mixed analysis service load assessment approach developed in the previous section (Eq. 7). This approach yields a conservative but significantly more accurate prediction, with the calculated strain being only 6% greater than the experimental strain at the maximum serviceability load applied.

For the mixed analysis results presented in Fig. 5, $p = 0.0046$ resulting in an $I_{eff} = 71\times10^6$ mm^4 (Eq. 8). For reference: the gross moment of inertia of the concrete slab, ignoring the reinforcing steel $I_g = 250\times10^6$ mm^4; the fully cracked moment of inertia $I_{cr} = 28.4\times10^6$ mm^4; the Young's modulus of the concrete was determined experimentally to be 27450 MPa; and that of the steel was taken to be 200000 MPa. Because only five cycles of load was applied to each beam it was assumed that the steel-concrete interface would not have been polished and hence, the upper bound coefficient of friction of 0.95 was used to represent the test conditions. The net normal force across the interface used to determine F_{fric} was taken as half the applied load and half the total dead load of the concrete slab, as the design point was at the midspan. For a more conservative assessment, the compressive normal force due to the dead load of the concrete deck may be ignored.

In the assessment of a typical multi-span slab-on-girder bridge, the new live load stress is obtained once the maximum tensile stress at the midspan of one of the simply supported spans has been determined. For the case of multiple point (axle) loads traversing the span, the maximum moment will occur near midspan when one of the loads is at the midspan, which can be determined using the principal of superposition and influence lines. To simplify the calculation of F_{fric}, a safe approach is to ignore the loads not at the midspan as they will ultimately have little effect on the magnitude of F_{fric} and the prediction will remain conservative and the error minimal. The resulting increase in fatigue life of the beam due to the reduction in flexural stresses as a result of interface friction will depend upon local design standards.

For example, the increase in fatigue endurance due to the reduction in stress can be quantified using the following well-known relationship (Oehlers and Bradford 1995).

$$N = CR^{-m} \tag{10}$$

where N is the endurance or number of cycles to failure, C is a fatigue constant, R is the stress range and, m is the fatigue exponent which can be taken as 3.0 for the steel beam in this example. From Fig. 5, the slab-on-girder mixed analysis service load assessment approach predicted a 13% reduction in the maximum steel stress from that of a no-interaction analysis assuming a fully cracked concrete section. Hence, from Eq. (10), $N = C(1–0.13)^{-3} = (1.51)C$ implying that the fatigue endurance of the steel beam is increased by 51% when interface friction is considered in a mixed analysis approach. Similarly, a 19% reduction in the maximum tensile steel stress is obtained compared to that assuming the steel beam alone resists the applied load resulting in a potential 88% increase in fatigue endurance from that which was most likely anticipated at the design stage for this type of structure. Other fatigue damage equations are available (Oehlers and Bradford 1995) that can allow for increased loads or the effect of rehabilitation measures on the remaining fatigue endurance of such structures, where the appropriate stress ranges can now be calculated more accurately using the slab-on-girder mixed analysis service load assessment approach presented in this paper.

6. Conclusions

The effect of unintentional composite action on the response of slab-on-girder bridge beams resulting from friction acting along the steel-concrete interface was investigated experimentally. The experimental results confirmed that interface friction is not effective in increasing the flexural capacity of slab-on-girder beams and consequently, should not be considered in an assessment.

However, the tests showed that interface friction reduced the flexural stresses under serviceability loads, compared to what is predicted from a standard no-interaction analysis assuming the concrete slab is fully cracked. This has led to the development of a new technique called the slab-on-girder mixed analysis service load assessment approach that can much more accurately predict the flexural stress distribution. Concrete cracking, which has a significant effect on the response of these structures, is allowed for by introducing a simple model for the effective moment of inertia of a rectangular cracked reinforced concrete section. Based on experimental testing by others, a lower bound coefficient of friction between the steel and concrete components of 0.7 is recommended in the assessment of existing structures.

The resulting reduced tensile stress range predicted by the slab-on-girder mixed analysis service load assessment approach is used in a fatigue damage equation to predict the remaining strength or endurance of the structure. This technique provides a simple but much more accurate analytical technique that can be used by engineers in the assessment of existing slab-on-girder bridges, that will reduce the number of full-scale load tests required. If, however, the analysis does not show that the remaining strength or endurance of the structure is adequate, then a load test of the bridge could be undertaken to determine whether the factors other than unintentional composite action increases the strength or endurance to the required level.

The technique developed can also be easily used to predict the reduced deflections due to unintentional composite action and to determine the effectiveness of strengthening techniques should they be required.

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