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Technical Note

Partial-interaction fatigue assessment of stud shear connectors in composite bridge beams

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Abstract. There is a growing demand to assess the remaining strength and endurance of existing composite steel and concrete bridge beams due to the aging infrastructure, increases in permissible vehicle weights and increases in their frequencies. As codes are generally dedicated to the design of new structures, new procedures are required to aid in the assessment of existing bridges to ensure that they are utilised to the full. In this paper, simple expressions are presented to perform partial-interaction analyses directly from full-interaction analyses, so that the beneficial effect of partial-interaction on the shear forces on the shear connectors can be utilised in assessment to extend the fatigue life of simply supported bridge beams and to determine the effect of remedial work if necessary. Use of the assessment technique is described by way of an illustrative example.

Key words: steel-concrete beams; partial-interaction; fatigue assessment; longitudinal shear forces.

1. Introduction

The design of new composite steel and concrete bridge beams through codes of practice is invariably based on full-interaction analyses (Oehlers and Bradford 1995 & 1999, Johnson 1994, Johnson and Buckby 1986) that assume that there is no slip between the concrete component and the steel component, even though numerous published tests (Oehlers and Coughlan 1986, Slutter and Fisher 1966, Mainstone and Menzies 1967) have clearly shown that mechanical shear connectors must slip in order to resist shear forces and that the magnitude of this slip continually increases under cyclic loads. However, the full-interaction design approach has been shown to give a safe design for the shear connectors (Johnson 2000) because a full-interaction analysis does not allow for the reduction in the shear flow force along the steel-concrete interface due to partial-interaction (Oehlers and Bradford 1995, Johnson 1994, Newmark *et al.* 1951), incremental set (Oehlers and Bradford 1995, Mainstone and Menzies 1967) and friction (Oehlers and Bradford 1995 & 1999, Oehlers *et al.* 2000). However, for the assessment of existing simply supported bridges for increased live loads, extended lives or remedial work, more accurate analyses may be required to ensure the most efficient use of the structure. A simple procedure (Seracino 2000, Oehlers and Seracino 2002) is described in this paper that allows the beneficial effects of partial-interaction on the shear flow force distribution to be deduced from standard full-interaction analyses.

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A brief description is first given of a fatigue assessment procedure (Oehlers *et al.* 2000, Oehlers and Foley 1985) that allows for the reduction in strength of stud shear connectors subjected to fatigue loads. This is then followed by a simplified procedure for determining the complex partial-interaction shear flow forces from full-interaction analyses which is then applied in an example.

2. Residual strength and endurance fatigue assessment

Tests (Oehlers 1990, Gattesco and Giuriani 1996) have shown that the shear strengths of stud shear connectors reduce immediately cyclic loads are applied to them and that this reduction in strength is linear. Variations in the residual strengths are shown schematically in Fig. 1 where for example, the application of a range of cyclic shear load R_1 at a peak load P_1 on a stud shear connector of static strength D_{st} causes the shear connector to fail at an endurance E_1 when the residual strength $(D_{res})_1$ reduces to that of the peak load P_1. Similarly, increasing the range to R_2 and reducing the peak to P_2 as shown causes failure at E_2 cycles.

The variations in the residual strengths in Fig. 1 can be quantified using the concept of the asymptotic endurance E_a (Oehlers 1990), which is simply derived from a linear extrapolation as shown. The asymptotic endurance has been quantified (Oehlers 1990) for stud shear connectors and can be given in the form

$$E_a = C\left(\frac{R}{D_{st}}\right)^{-m} \tag{1}$$

where the fatigue endurance exponent m and the fatigue constant C can have values of 5.1 and $10^{3.1}$ respectively, depending on the test data being processed (Johnson 2000, Oehlers 1990). The behaviour of the shear connectors represented by Fig. 1 can be incorporated into the generic fatigue equation (Oehlers and Bradford 1995 & 1999, Oehlers *et al.* 2000) which can be written in the following

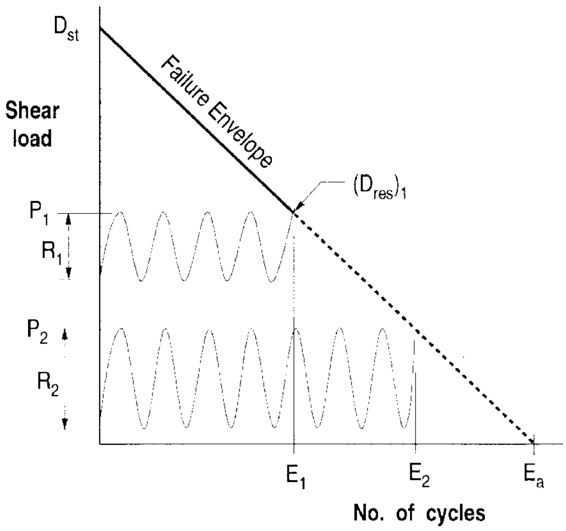

Fig. 1 Asymptotic endurances and residual strengths

form that is suitable for assessment

$$Q_{res} = Q_{st} - \frac{\sum_{y=1}^{y=j} (TF_f L_f)_y}{Q_{st}^{m-1} C} \tag{2}$$

where Q_{res} is the residual or remaining shear flow strength after fatigue loads have been applied and Q_{st} is the shear flow strength when the structure was first built.

The parameter $TF_f L_f$ in Eq. (2) will be referred to as a fatigue zone as it is a duration of T_y fatigue vehicle traversals during which both the load constant $(L_f)_y$ and the force constant $(F_f)_y$ are constant. The load constant $(L_f)_y$ can be derived from the spectrum of fatigue vehicle loads (Johnson and Buckby 1986, BS5400 1980) that the bridge is subjected to and is given by

$$L_f = \sum_{x=1}^{x=i} B_x W_x^m \tag{3}$$

where W_x is the weight of the fatigue vehicle as a proportion of the weight of an arbitrary standard fatigue vehicle and which has a probability of occurrence of B_x such that $\sum B_x = 1$. The force constant $(F_f)_y$ is derived from a spectrum of forces (Oehlers and Bradford 1995) and is given by

$$F_f = \sum_{y=1}^{y=i} f_y (q_{range})_y^m \tag{4}$$

where $(q_{range})_y$ is a range of the shear flow force when the standard fatigue vehicle is moved across the bridge and which occurs f_y times per standard fatigue vehicle traversal. Hence a fatigue zone is a period of time in which the range of vehicles traversing the bridge and the range of forces within the bridge remain constant. If the ranges of vehicles are changed by say placing a weight restriction on the bridge or the ranges of internal forces are changed by say strengthening the bridge then this signifies a new fatigue zone. It is also worth noting that it has been shown (Gosh *et al.* 1996) that the sequence of application of the fatigue zones in Eq. (2) does not affect the residual strength because of the linear variation in the residual strengths in Fig. 1.

The aim of this paper is to accurately determine the ranges of the shear flow forces, q_{range} in Eq. (4), when the standard fatigue vehicle is moved across the bridge. Once this is determined, then Eq. (2) can be used to predict the residual strengths of the shear connectors Q_{res} after any combination or sequence of fatigue loading. Alternatively, Eq. (2) can be rearranged to determine the remaining number of fatigue vehicle traversals to failure T_y that will cause the residual strength Q_{res} to reach a minimum requirement. The procedures will be illustrated using the case of a two-axle vehicle traversing a simply supported composite beam.

3. Partial-interaction behaviour

Partial-interaction analyses account for the realistic stiffness of the shear connection which results in slip at the concrete-steel interface. This is beneficial as the forces resisted by the stud shear connectors are reduced compared to the predictions from a full-interaction analysis. A finite element computer program was developed (Seracino 2000) that can model the partial-interaction behaviour of composite beams allowing for the non-linear behaviour of the longitudinal shear connection. The results of a simulation (Seracino 2000) for a single concentrated load of 320 kN acting at the quarter-span of a 50.4 m long beam with a cross-sectional geometry such that $A_c\bar{y}/I_{nc} = 0.504 \times 10^{-3}$ mm^{-1} is given by line B in Fig. 2.

In contrast to the previous partial-interaction approach, the results of a full-interaction analysis are shown as lines A in Fig. 2. The standard full-interaction approach, which is used in design, assumes that the stiffness of the shear connection is infinite, hence, there is no interfacial slip between the steel and concrete components. Therefore, the full-interaction shear flow force q_{fi}, that is the longitudinal shear force per unit length along the steel-concrete interface, can be determined from the following well known equation (Oehlers and Bradford 1995, Johnson 1994).

$$q_{fi} = \frac{VA_c\bar{y}}{I_{nc}} \tag{5}$$

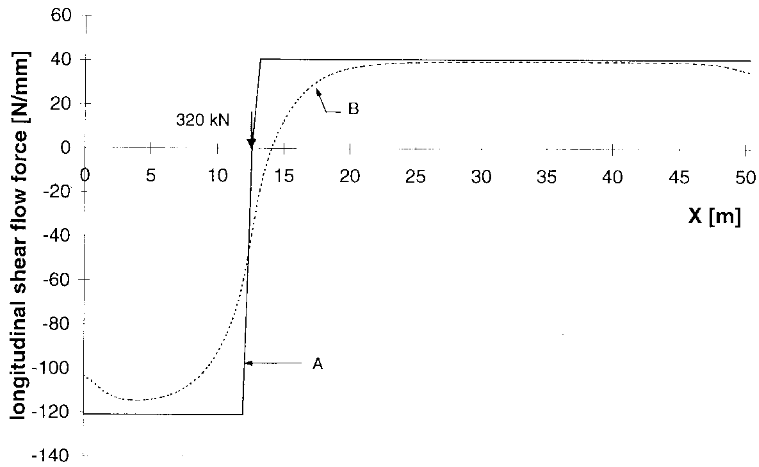

Fig. 2 Shear flow forces for a stationary load

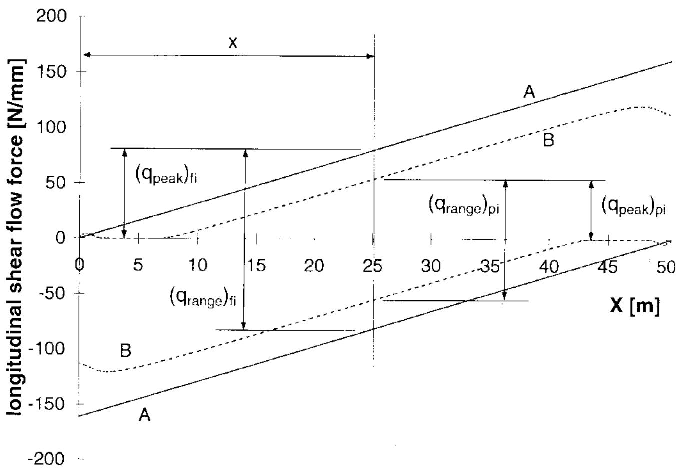

Fig. 3 Shear flow force envelopes for a moving concentrated load

where V is the vertical shear force, A_c is the cross-sectional area of the concrete component, $\bar{y}$ is the distance between the centroid of the concrete component and the centroid of the transformed composite section, and I_{nc} is the second moment of area of the transformed concrete composite section. A qualitative comparison of the partial-interaction and full-interaction results in Fig. 2 for this stationary concentrated load would suggest that the effect of partial-interaction is not significant for beams subjected to longitudinally stationary loads.

Moving the concentrated load across the beam produces the full-interaction and partial-interaction shear flow force envelopes in Fig. 3. In contrast to the previous stationary load results (Fig. 2), it can be seen that for moving loads, the partial-interaction shear flow force $(q_{range})_{pi}$ (Fig. 3) is now substantially less than $(q_{range})_{fi}$. Similarly, the peak partial-interaction unidirectional shear flow force $(q_{peak})_{pi}$ is less than $(q_{peak})_{fi}$. Hence, allowing for the reduction in shear flow due to partial-interaction in composite beams subjected to longitudinally traversing fatigue vehicles will substantially improve the endurance and strength which is the aim of the following sections.

4. Simplified partial-interaction models

The partial-interaction theory that was used to develop the following mathematical models was first published in 1951 (Newmark *et al.* 1951). The parameters used in the mathematical models can be found in Johnson (1994). Derivation of the partial-interaction theory used to develop the simplified models can also be found elsewhere (Oehlers and Seracino 2002, Seracino *et al.* 2001, Seracino 2000).

4.1 Simplified model for the partial-interaction range reduction factor

The reduction in the full-interaction shear flow range due to partial-interaction is defined by the following range reduction factor

$$RF_R = \frac{(q_{range})_{pi}}{(q_{range})_{fi}} \tag{6}$$

It can be seen in Fig. 4 from both the mathematical and computer simulations (Seracino 2000) that the distribution of RF_R is symmetrical about the mid-span of the simply supported beam for the traversal of a single concentrated load. It is a maximum at the supports, then gradually reduces inwards until a relatively constant minimum value is maintained over the mid-span portion of the beam. The proposed simplified model, also shown in Fig. 4, determines the reduction factor at the supports $(RF_R)_{sup}$ and the location along the beam l_{const} where the reduction factor becomes constant at $(RF_R)_{const}$; straight line segments are used to connect these points.

The simplified expression that is used to estimate RF_R at the supports is

$$(RF_R)_{sup} = 1 + \frac{1}{\alpha L}\ln\left(\frac{1}{\alpha L}\right) - \frac{2}{(\alpha L)^2 + 1} \tag{7}$$

which is only a function of the length of the beam L and the parameter α which is a function of the cross-sectional geometric and material properties of the composite beam and the connection stiffness.

The point l_{const} that defines the location where RF_R first becomes constant when measured from the supports is

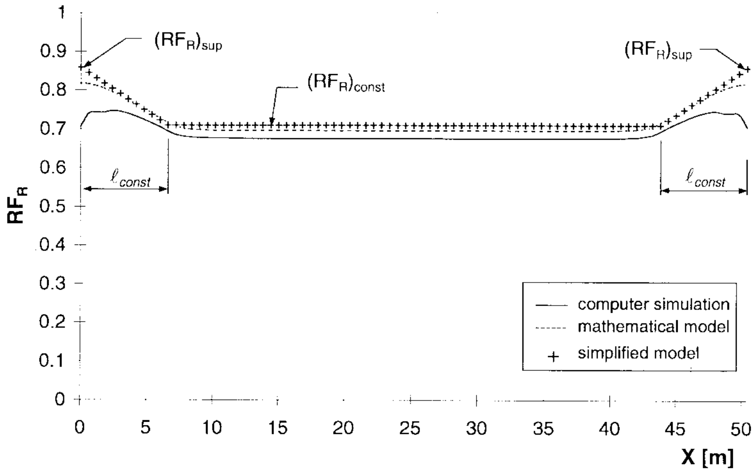

Fig. 4 Simplified shear flow range reduction factors RF_R

$$l_{const} = \frac{-1}{\alpha}\ln\left(\frac{1}{\alpha L}\right) \tag{8}$$

Finally, the constant magnitude of RF_R in the vicinity of the mid-span is

$$(RF_R)_{const} = 1 + \frac{1}{\alpha L}\left\{\ln\left[\frac{2}{(\alpha L)^2 + 1}\right] - 1\right\} \tag{9}$$

4.2 Reduction of the peak unidirectional partial-interaction shear flow

The remaining strength or endurance of stud shear connectors is also dependent on the peak unidirectional shear flow force as shown in Fig. 1. The peak unidirectional shear flow reduction factor is defined as

$$RF_P = \frac{(q_{peak})_{pi}}{(q_{peak})_{fi}} \tag{10}$$

Fig. 5 shows the distribution of RF_P obtained from a partial-interaction computer simulation resulting from the traversal of the 320 kN concentrated load along the 50.4 m long composite beam, as well as the partial-interaction theoretical distributions (Seracino 2000). As can be seen, there are theoretically two reduction factors for each design point, except at the mid-span. However, the governing peak unidirectional shear flow force to be used in the assessment will be the largest one, hence, the greater of the two reduction factors at a design point is the governing one.

It can be seen in Fig. 3 that the peak unidirectional shear flow force q_{peak} is related to the shear flow range q_{range}. From this relationship it was found (Seracino 2000) that the simplified mathematical equations that were used to predict RF_R in Eqs. (7) and (9) can also be used to model the reduction in the unidirectional shear flow RF_P as shown in Fig. 5. The variation in RF_P is defined by a bilinear variation fixed by $(RF_R)_{sup}$ at the supports and $(RF_R)_{const}$ at the mid-span.

The next section describes the use of the assessment technique by way of an example, where a two-axle vehicle traverses a simply supported bridge beam.

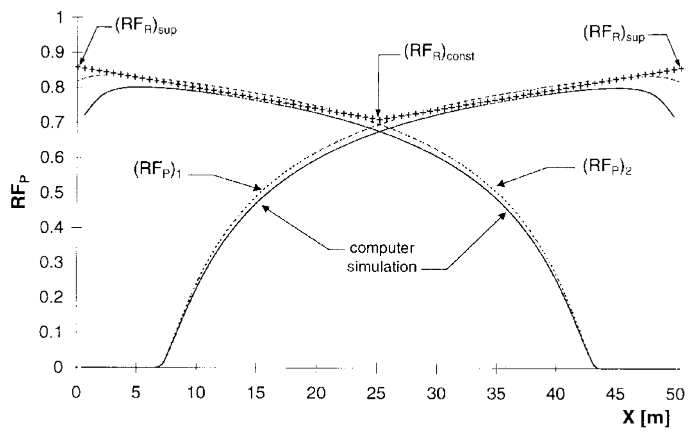

Fig. 5 Peak shear flow reduction factors RF_P

5. Fatigue assessment of a simply supported composite beam

The following example is used to illustrate the use of the assessment method to predict the remaining strength or endurance of the stud shear connectors.

Suppose that the 50.4 m long simply supported composite beam has been designed using the standard full-interaction analysis procedure for a fatigue life of 100 years or 200×10^6 fatigue vehicle traversals. The fatigue vehicle consisted of two 160 kN loads 7.8 m apart, and the cross-sectional geometry of the beam was such that $I_o = 3.80 \times 10^{10}$ mm^4 and (1/A') = 2.80×10^6 mm^2. The loading is such that, using the Reservoir Method (BS5400 1980) of cyclic counting to determine the equivalent set of cyclic forces producing the same fatigue damage, results in two equivalent cyclic ranges along the beam. At the right support, where the maximum range is located, the equivalent cyclic ranges are $(q_{range})_{fi,\,1} = 148.8$ N/mm and $(q_{range})_{fi,\,2} = 10.0$ N/mm, and the peak unidirectional shear flow force $(q_{peak})_{fi} = 80.6$ N/mm. To simplify the example, $(q_{range})_{fi,\,2}$ is ignored as it is very small compared to $(q_{range})_{fi,\,1}$ and, hence, has a negligible effect on the fatigue damage. The beam was designed for a maximum design overload $Q_{res} = 9(q_{peak})_{fi} = 725.4$ N/mm and the shear flow strength required at the start of the design life was $Q_{st} = 1750$ N/mm. A uniform distribution of connectors was used consisting of two rows of 22 mm diameter studs, with a static strength of 140 kN per stud, spaced at 160 mm along the length of the beam. In this example, $F_f = (1.0)(148.8)^{5.1} = 1.203 \times 10^{11}$ (N/mm)$^{5.1}$, L_f was taken as unity, and $\alpha = 0.483 \times 10^{-3}$ mm^{-1}.

If near the end of the original design life of 200 million fatigue vehicle traversals an assessment of the bridge is carried out, the simplified partial-interaction approach presented in this paper may be used to determine a more accurate estimate of the shear flow forces and hence, predict the remaining strength or endurance of the shear connectors. Substituting $\alpha L = 24.3$ into Eq. (7), $(RF_R)_{sup} = 0.865$, so that at the right support $(q_{range})_{pi} = (0.865)(148.8) = 128.7$ N/mm. As the design point under consideration is at the support, the same reduction factor applies to the peak unidirectional shear flow force, so that $(q_{peak})_{pi} = (0.865)(80.6) = 69.7$ N/mm. Similarly, using Eq. (9), $(RF_R)_{const} = 0.725$, and from Eq. (8), $l_{const} = 6.6$ m which must be adjusted by 7.8 m to allow for the distance between the two axle loads to give $l_{const} = 14.4$ m. From this, the range reduction factor distribution for the simplified partial-interaction approach can be determined as shown in Fig. 6.

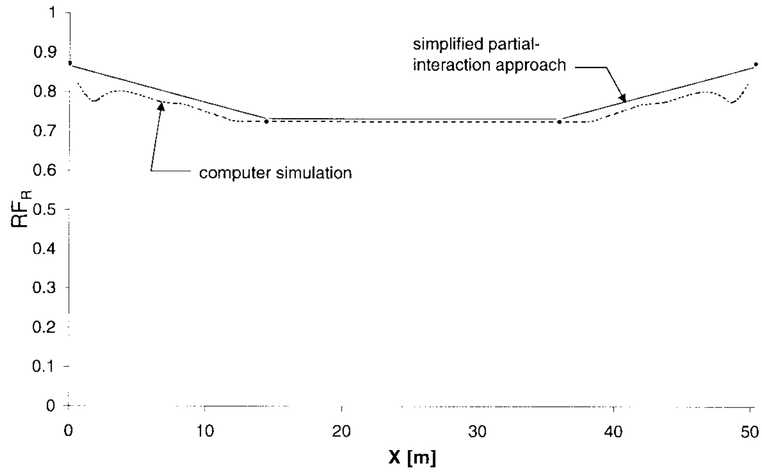

Fig. 6 Partial-interaction distribution of shear flow forces

Also shown in Fig. 6 is the distribution given by a partial-interaction computer simulation, which shows that the simplified method predicts conservative results over the length of the beam.

For the design point at the right support, the remaining endurance of the shear connection can now be found using Eq. (2). The force factor must be revised to $F_f = (1.0)(128.7)^{5.1} = 5.74 \times 10^{10}$ $(\text{N/mm})^{5.1}$ and the maximum design overload becomes $Q_{res} = 9 \times 69.7 = 627.3$ N/mm. Substituting the revised F_f and Q_{res} into Eq. (2) gives the following expression

$$T_2 = \frac{10^{3.12}(1750)^{5.1}\left(1 - \frac{627.3}{1750}\right) - 200 \times 10^6 (5.74 \times 10^{10})(1.0)}{5.74 \times 10^{10}(1.0)} \tag{11}$$

where the last term in the numerator of the right hand side represents the fatigue damage that has occurred, and the denominator is the fatigue damage that can still occur. Solving for the remaining endurance gives $T_2 = 310 \times 10^6$, that is, 310 million fatigue vehicles. If the number of fatigue vehicles will increase by 10% to 2.2 million per year, the remaining life of the shear connectors is 140 years. As an aside, if the reduction in the peak unidirectional shear flow force is not accounted for, T_2 reduces to 265×10^6 vehicles. Therefore, the reduction in the range alone accounted for approximately 85% of the increase in the remaining endurance of the shear connection.

If it is anticipated that the allowable weights of the fatigue vehicles will increase by 10% in the future, the load factor will increase by a factor of $1.1^{5.1} = 1.63$ so that it is revised to $L_f = (1.0)(1.63) = 1.63$. Furthermore, to obtain the same factor of safety, the maximum overload must be increased by 10% such that $Q_{res} = (1.1)(627.3) = 690.0$ N/mm. Therefore, the new remaining endurance can be found from the following expression

$$T_2 = \frac{10^{3.12}(1750)^{5.1}\left(1 - \frac{690.0}{1750}\right) - 200 \times 10^6 (5.74 \times 10^{10})(1.0)}{5.74 \times 10^{10}(1.63)} \tag{12}$$

where T_2 is calculated to be 172×10^6 vehicles and, hence, a remaining life of 78 years assuming 2.2 million fatigue vehicle traversals per year.

6. Conclusions

A simple partial-interaction hand technique has been presented for the assessment of the remaining strength or endurance of the shear connectors in simply supported composite steel-concrete bridge beams. It has been shown that even relatively small reductions in the range of load resisted by the shear connectors results in a significant increase in the remaining strength or endurance of the shear connection.

Acknowledgements

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Notation

A	: cross-sectional area of a component
$(A')^{-1}$	: $d_c^2 + I_o\left(\frac{n}{A_c} + \frac{1}{A_s}\right)$
B	: probability of occurrence of a fatigue vehicle
C	: fatigue constant
c	: concrete component when used as a subscript
const	: constant when used as a subscript
D_{res}	: residual strength of a stud shear connector
D_{st}	: static strength of a stud shear connector
d_c	: distance between the centroids of the steel and concrete components
E	: modulus of elasticity; endurance
E_a	: asymptotic endurance
F_f	: force factor
f	: frequency of q_{range} per standard fatigue vehicle traversal
fi	: full-interaction when used as a subscript
I	: second moment of area
I_{nc}	: second moment of area of the transformed concrete composite section
I_o	: $I_s + \frac{I_c}{n}$
k	: stiffness of the stud shear connectors
L	: length of a simply supported composite beam
L_f	: load factor
l_{const}	: distance from left support where RF_R becomes constant
m	: fatigue endurance exponent
n	: $\frac{E_s}{E_c}$
P	: peak unidirectional shear flow force
p	: stud shear connector spacing
pi	: partial-interaction when used as a subscript
Q_{st}	: shear flow strength of the stud shear connectors prior to cyclic loading
Q_{res}	: residual strength of the stud shear connectors after cyclic loading
q_{peak}	: peak unidirectional shear flow force
q_{range}	: range of the shear flow force due to the traversal of the standard fatigue vehicle
R	: range of cyclic shear acting on the stud shear connectors
RF_P	: unidirectional shear flow reduction factor
RF_R	: range reduction factor
s	: steel component when used as a subscript
sup	: support when used as a subscript
T	: number of fatigue vehicle traversals in a fatigue zone
V	: vertical shear force
W	: weight of a fatigue vehicle as a proportion of the weight of the standard fatigue vehicle
$\bar{y}$	: distance between the centroid of the concrete component and the centroid of the transformed composite section
α	: $\sqrt{\frac{k}{pE_sI_oA'}}$