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Fatigue in Stud Shear Connectors

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Summary

The results of a numerical simulation of the behavior of steel and concrete composite beams subjected to cyclic loads are here presented. Both partial and complete shear connections were considered. The results show that no significant differences in slip occur with partial interaction. Two groups of beam specimens were numerically tested concerning either connectors distributed according to the longitudinal shear loads or uniformly spaced. The second group showed values of the slip considerably greater.

1. Introduction

In steel and concrete composite beams subjected to cyclic loads a particular attention has to be paid to the connection because it may reach a premature failure due to fatigue. If the connection during loading cycles remains in the elastic range a large number of cycles is needed before it collapses (high-cycle fatigue) on the contrary, if inelastic deformations of the connection are involved, the failure may occur after a limited number of cycles (low-cycle fatigue).

Normally the connections are designed to be able to transmit a longitudinal shear force equal to the difference between the resisting longitudinal forces, in either the steel member or the concrete slab (the lesser), at two adjacent sections of maximum moment or free end (complete shear connection). However, sometimes it is useful or necessary to provide a partial shear connection. In fact, when precast elements are used for the concrete slab it is quite difficult to obtain complete shear connections because for constructional needs only limited space is available to allocate the connectors. Moreover, often the composite system is needed mainly to increase the stiffness of the structure so that a complete shear connection may cause an excessive resistance.

Current codes [1] for composite bridges do not allow the use of partial shear connections and moreover the connectors have to be spaced according to the longitudinal shear force so as to enable the use of the constant stress approach for fatigue. This approach is based on the hypothesis of linear elastic behavior of elements (high-cycle fatigue approach).

As a matter of fact, the load-slip relationship of the connector is nonlinear even for very low values of the load. Moreover at the end of the reloading branch of each cycle an increment of slip Δs_0 is accumulated due to the progressive damage both in the concrete in front of the stud and in the shank of the stud.

On the basis of such considerations the scope of the present research is to simulate the connector behavior in a beam by means of a numerical procedure. The investigation concerns bridge-type beams subjected, for simplicity, to a cyclic uniformly distributed load and arranged with different

degree of connection in order to check if partial shear connection is really unproposable for bridges.
To emphasize the problem a low-frequency heavy load was considered as reference in the simulations so to involve significant nonlinear displacements.
Moreover such a procedure allows to obtain the slip history of the studs in the beam which is indispensable for the experimental study of the resistance of studs to fatigue when significant inelastic deformations are involved. In fact, as stated in [2], in these cases the tests have to be performed using a strain-control procedure instead of the common stress-control one. The slip history used in that paper [2] was obtained with the same numerical procedure but using a more rough load-slip relationship for connectors [3].

2. Numerical model.

A numerical approach based on the four noded finite element of Fig. 1 was adopted in the simulation [3]. Each element has 12 degrees of freedom which become 8 if the uplift of concrete slab is neglected and the curvature of concrete element and steel beam are the same.

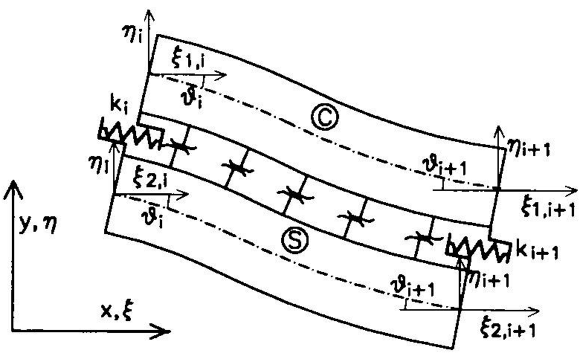

Fig. 1 - Four noded finite element.

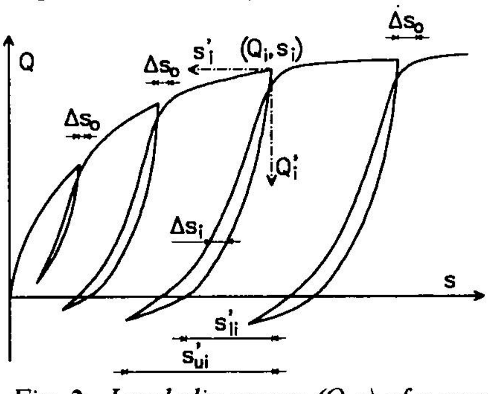

Fig. 2 - Load-slip curves (Q-s) of a connector for repeated loading.

The concrete (C) and the steel (S) are assumed as linear elastic materials while for the connection the following load-slip relationships are assumed [3,4]. In particular the monotonic curve is described by the function

$$Q = \alpha \cdot (1 - e^{-\frac{\beta \cdot s}{\alpha}}) + \gamma \cdot s \qquad (1)$$

where Q is the shear force of the connector, s is the slip between the concrete slab and the steel beam and the coefficients α, β, γ are constants to be experimentally determined.
The unloading curves refer to a local axis with the origin in points (Q_i, s_i) where the unloading starts (Fig. 2)

$$Q'_i = Q_i \cdot \lambda \cdot (1 - e^{-\frac{\eta \cdot z_i}{\lambda}} + \frac{\delta}{\lambda} \cdot z_i) \qquad (with\ z_i = \frac{s'_i}{s'_{li}}) \tag{2}$$

where s'_{li} is the slip, referred to the local axis, corresponding to a zero value of the load and it depends to the shear load Q_i

$$s'_{li} = c_1 \cdot Q_i^3 + c_2 \cdot Q_i, \tag{3}$$

η has the following expression

$$\eta = b_1 \cdot Q_i - b_2. \tag{4}$$

The coefficients λ (Eq. 2), c_1, c_2 (Eq. 3) and b_1, b_2 (Eq. 4) have to be experimentally determined. The value of coefficient δ is obtained by Eq. 2 imposing $Q'_i = Q_i$ for $z_i = 1$ ($s'_i = s'_{li}$). The value of the slip at the end of the unloading s'_{li} varies with the number of cycles according to the relationship [4]

$$s'^{j}_{li} = s'^{1}_{li} \cdot (1 + \rho \cdot \frac{(j-1)^{\varepsilon}}{25 + (j-1)^{\varepsilon}}) \tag{5}$$

where ρ and ε are constants and the suffix j means cycle number j.
The reloading curves are referred to the same local axis. Each point of the curves is obtained by an horizontal translation Δs_i (Fig. 2), starting from the unloading curve, which depends on s'_{ui} according to the relationship

$$\Delta s_i = \xi \cdot (s'_{ui} - s'_i), \tag{6}$$

where s'_{ui} represents the slip value at the beginning of the reloading. ξ can be expressed as a function of s'_i/s'_{li} in the following way

$$\xi = c_3 \cdot (1 - e^{-\frac{c_4 \cdot z_i}{c_3}}) + c_5 \cdot z_i + c_6, \tag{7}$$

c_3, c_4 , c_5 are constants and c_6 has the relationship

$$c_6 = \frac{\Delta s_{oi}}{s'_{ui}}. \tag{8}$$

The increment in slip Δs_{oi} at the end of the reloading curve, which represents the cumulative damage at each cycle, may be determined in this way

$$\Delta s^{j}_{oi} = \frac{Q_i \cdot s'^{j}_{ui}}{s'^{j}_{li}} \cdot (\frac{\nu - \mu}{j} + \mu) \tag{9}$$

where ν and μ are constants. The coefficients c_3 and c_4 vary with the number of cycles in the following way

$$c^{j}_3 = c^{1}_3 - (\frac{\Delta s^{1}_{oi}}{s'^{1}_{ui}} - \frac{\Delta s^{j}_{oi}}{s'^{j}_{ui}}) \tag{10}$$

$$c^{j}_4 = \frac{c^{j}_3}{c^{1}_3} \cdot c^{1}_4. \tag{11}$$

3. Specimen details.

The study concerns simply supported bridge-type beams with the geometric characteristics illustrated in Fig. 3. The yielding stress of structural steel was $f_{ys} = 355$ MPa ($\gamma_s = 1.00$), and the compressive strength of concrete was f_{ck} = 30 MPa (γ_c = 1.50). The coefficients needed to describe the load-slip of connectors under repeated loads were derived from experimental results [5] and they are reported in Table 1. Also the geometric and mechanical characteristics of stud connectors are indicated in the same table.

Characteristics of studs		Load-slip relationship coefficients			
Shank diameter	ϕ = 19 mm	Monotonic curve	Unloading curves	Reloading curves	Damage parameters
Yielding stress	f_y = 350 MPa				
Ult. tensile strength	f_t = 450 MPa	α = 82 kN	λ = 0.90	$c_3 = -c_6$	ε = 0.85
		β = 230 kN/mm	b_1 = 0.054 kN^{-1}	c_4 = 2.3	ρ = 0.31
Concrete comp.strength	f_{ck} = 30 MPa	γ = 5 kN/mm	b_2 = 1.34	c_5 = 0.4	$\nu = 1.16 \cdot 10^{-4}$ mm/kN
			$c_1 = 9.2 \cdot 10^{-7}$ mm/kN^3		$\mu = 1.7 \cdot 10^{-5}$ mm/kN
Exp. stud capacity [4]	Q_u = 100 kN		$c_2 = 9.0 \cdot 10^{-4}$ mm/kN		

Table 1 - Characteristics of stud connectors and load-slip relationship coefficients.

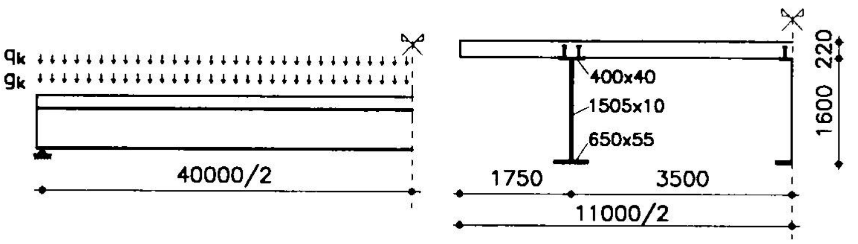

Fig. 3 - Geometrical characteristics of bridge-type beam considered.

As aforesaid the beam was subjected to cyclic uniformly distributed loads which vary between zero and a maximum value. It is supposed that the structure be built without the use of props so that the own weight g_k of the composite beam was supported by the steel member alone. The own weight (g_k~25 kN/m per each single beam), then, was not considered in the analyses.
Five different degrees of shear connection were assumed for the beams (N/N_f = 0.6 ÷ 1.0) and the connectors were arranged either following the longitudinal shear diagram (triangular distribution) or equally sspaced (uniform distribution).
The load applied to the beams with complete shear connection was the maximum service load (on a single beam) for a three lane bridge according to the Italian code (q_k~56 kN/m). The steel member, the concrete slab and the connection were designed on the basis of the ultimate load associated to the cited service loads (γ_G = 1.35, γ_Q = 1.50).
The same geometric characteristics for concrete slab and steel beam were assumed for the specimens (beams) with partial shear connection. The load applied was derived from the equilibrium method [1] on the critical section (maximum moment). The loads evaluated in this way are reported in Table 2.

4. Results

The numerical simulations concern bridge-type beams with five different degrees of connection and with two types of arrangement of studs along the span (triangular and uniformly distributed). The analyses were conducted up to 2000 cycles so as to investigate if the solutions tend to an almost stable value, in terms of slip or shear force, in the connection. It has to be noted that the Eq. (9), representing the cumulative damage in the connection, do not include the fast increase in damage which precede the stud failure [5,6]. So that the results which can be obtained with such a

N/N_f	Number of studs	Load q_k [kN/m]	s^1_{max} [mm]	s^1_{min} [mm]	s^n_{max} [mm]	s^n_{min} [mm]	s^n_{min}/s^n_{max}
Beams with studs arranged as the longitudinal shear							
1.00	255	56.00	0.311	0.161	0.612	0.420	0.685
0.90	230	54.12	0.356	0.179	0.643	0.406	0.631
0.80	204	52.16	0.417	0.220	0.690	0.398	0.577
0.70	179	49.07	0.483	0.264	0.736	0.384	0.520
0.60	153	44.56	0.545	0.307	0.771	0.363	0.470
Beams with studs equally spaced							
1.00	255	56.00	0.990	0.345	1.266	0.462	0.365
0.90	230	54.12	1.160	0.397	1.420	0.482	0.340
0.80	204	52.16	1.407	0.477	1.650	0.515	0.312
0.70	179	49.07	1.658	0.562	1.880	0.559	0.297
0.60	153	44.56	1.860	0.627	2.057	0.585	0.285

n is equal to 2000 cycles.

Table 2 - Results concerning the beams studied.

simulation are reliable up to 2/3÷3/4 of the connector life.

The results concerning the distribution of studs according to the longitudinal shear force (triangular distribution) are plotted in Fig. 4a. In particular in the figure the variation of the maximum slip of the extreme connectors with the number of cycles is shown. It is possible to note that the slip increases significantly in the first 300÷400 cycles and then tends to an almost constant value. The minimum slip (value of the slip at each load removal) varies similarly to the maximum slip as can be seen in Table 2.

The increase in maximum slip is less pronounced for partial shear connections ($N/N_f = 0.6$ - $s^n_{max}/s^1_{max} = 1.41$) than for complete shear connection ($s^n_{max}/s^1_{max} = 1.97$). So that the difference between the maximum slip at $n = 2000$ cycles of the beam with degree of connection $N/N_f = 0.6$ and that of the beam with full interaction ($N/N_f = 1.0$) is quite limited (~1.26).

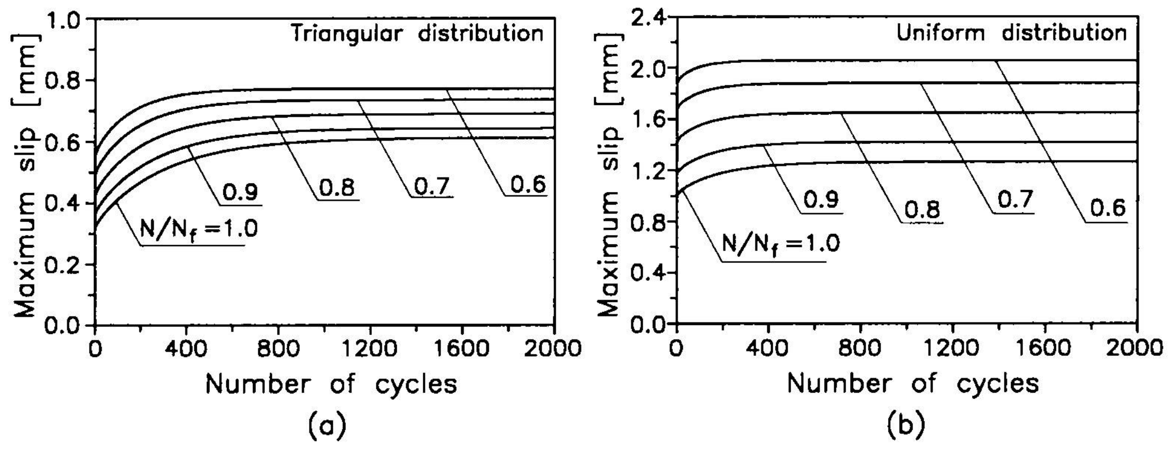

Fig. 4 - Maximum slip versus number of cycles: triangular a) and equally spaced studs b).

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In Table 2 are also reported the peak values of the slip (s_{max}, s_{min}) of the extreme connectors of the beam both at the first cycle and at the 2000-th cycle. In the last column of the table the values of the ratio between the minimum and the maximum slip at the 2000-th cycle are reported.
The curves of the maximum slip versus the number of cycles for beams with equally spaced connectors are plotted in Fig. 4b. Also these curves tend to an almost constant value of the slip after 2000 cycles. The increase in slip with cycles is more limited than in Fig. 4a because a greater redistribution of the shear force along the span is possible (the connectors close to midspan are initially very little engaged).
The principal results are summarized in Table 2. The values of the slip in these cases are significant and then considerable inelastic deformations are involved in the connectors at each cycle so that it is likely to occur the failure of the connectors after a low number of cycles (low-cycle fatigue) [2].
The loads considered are heavy repeated loads which may be present on the bridge only some thousands times during the structure life but the scope of the research was to investigate the effects under such severe loads. Actually at these loads all the other loads with higher frequency has to be added and then to consider the combined effect.

5. Conclusions

The study refers to low-frequency heavy loads and considers five different degrees of connection. The results evidence that there is a considerable increase in slip in the first 300÷400 cycles and then it tends to an almost constant value.
The changes between different degrees of interaction, in case of triangular distribution of the studs, are not very large so that it seems reasonable to considere partial shear connections also for bridges.
The case with equally spaced connectors indicate very large values of the slip even in the case of complete shear connection.
This early results are part of a study which aims to increase the knowledge on the problem of fatigue in the connection of composite systems. Moreover this results provide important information on the slip history of the connectors in the beam which is needed to perform strain-control experimental tests on single connectors [2].

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