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Low-Cycle Behaviour and Analysis of Steel-Concrete Composite Substructures

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Summary

Tests and analyses of steel-concrete composite structures subjected to alternate loads are proposed as part of an investigation on aseismic design of composite systems. Hence, quasi-static cyclic and pseudo-dynamic tests on composite beams with full and partial shear connection as well as complementary monotonic and cyclic tests on pull-push specimens were carried out. Moreover, two-dimensional finite element analyses based on smeared-crack formulations including discrete stud connectors and bond were performed. The paper presents some significant results to date.

1. Beam-Column Substructures

The partial action between concrete deck and steel girder within composite framing systems in earthquake prone zones can provide more choice for the designer and may reduce costs. However, the assessment of frame performance with partial shear connection (PSC) composite beams requires beam finite elements embodying complex hysteresis analytical models. So far, few relevant experimental data on PSC beams subjected to low-cycle alternate loading are available.

1.1 Test Subassemblages, Procedures and Results

Four among six full scale composite beam specimens with PSC and full shear connection (FSC) were built and tested by Bursi and Ballerini [1]. According to EC-4 [2], a conventional degree of shear connection N/N_f equal to 0.68 and 1.32 was estimated for the PSC and FSC beam, respectively. The two companion PSC beams characterised by a N/N_f ratio of 0.45 are under testing. The geometrical characteristics of the composite substructures as well as part of the measurement apparatus are highlighted in Fig. 1. The beam axial displacement is detected by means of an external LVDT at the steel beam centroid whilst the slip between the steel beam and the composite slab is collected by means of coupled LVDTs located at Sections 1-4. Other related information are collected in [1]. Quasi-static cyclic lateral displacements were applied to the specimens according to the ECCS procedure [2] as implied by Fig. 1, whilst pseudo-dynamic tests were performed on companion specimens according to the test set-up highlighted in Fig. 2.
For conciseness, only some results are presented in what follows. The hysteresis loops of the reaction force developed by the FSC substructure *versus* the controlled displacement are plotted in Fig. 3a. The inelastic hysteretic behaviour exhibited by the specimen is governed by steel beam yielding for positive (pull) loads and rebar yielding as well as concrete fracturing for negative (push) loads. Web and flange buckling occurred at the first negative hemicycle characterised by a

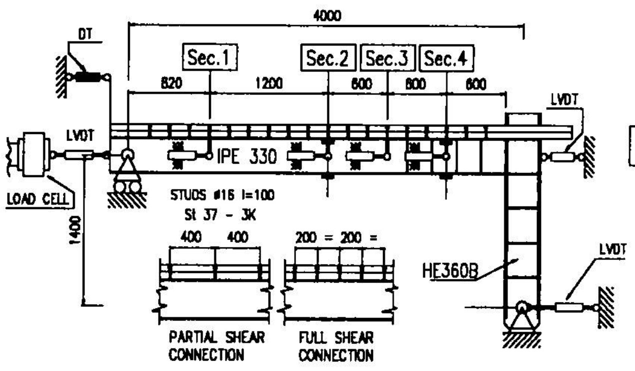

Fig. 1 Lay-out of substructure with full shear connection and relevant measurement apparatus

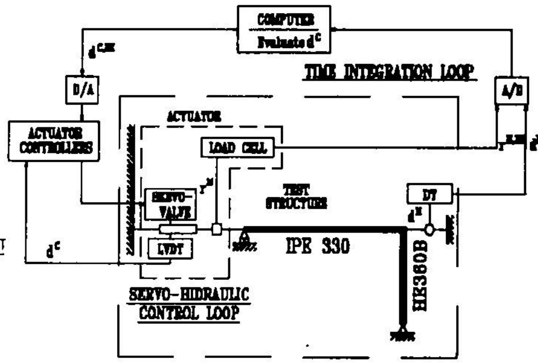

Fig. 2 Lay-out of the pseudo-dynamic test set-up

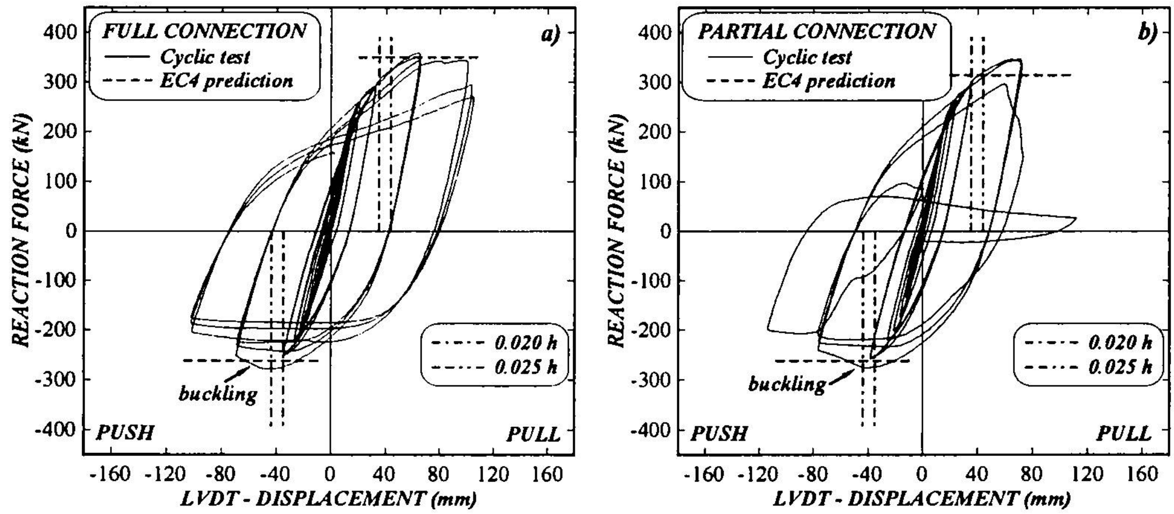

Fig. 3 Cyclic hysteresis loops of reaction force vs. controlled displacement of substructure with: a) full shear connection; b) partial shear connection

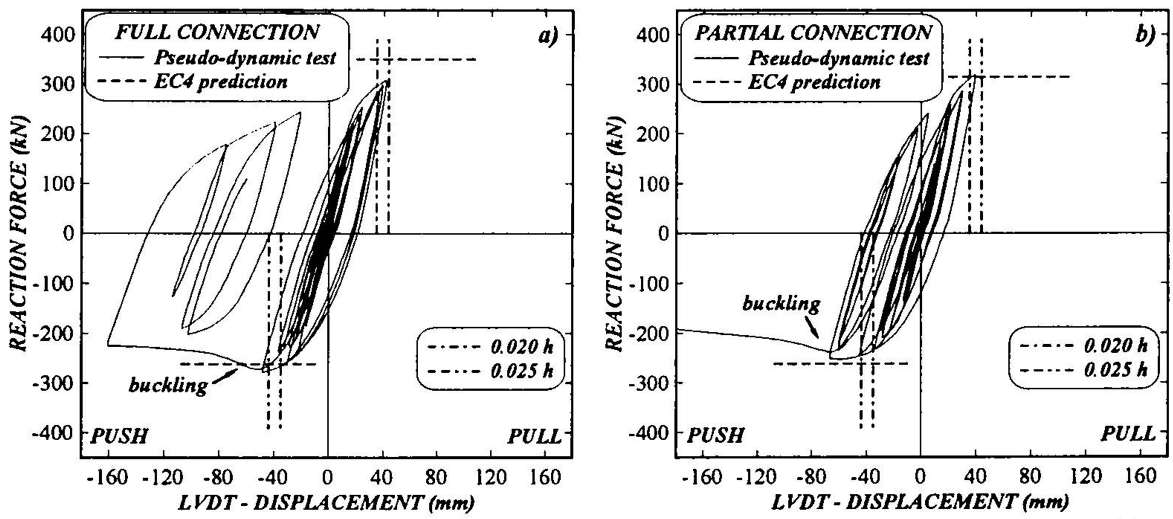

Fig. 4 Pseudodynamic hysteresis loops of reaction force vs. controlled displacement of substructure with: a) full shear connection; b) partial shear connection

displacement ductility factor of 4. In this respect, if one considers the interstorey drift limits corresponding to the ultimate limit state, 2.0%, as well as to the demolition state, 2.5%, respectively, under the assumption of a storey height of 3.5 m, the specimen behaviour appears to be satisfactory. The mean reaction force without safety factors as predicted by EC-4 [2] and corresponding to the maximum resistance of the composite beam, is indicated in Fig. 3a. One can observe the shortcoming of EC-4 prediction when cyclic loads are involved. The corresponding reaction force-displacement loops germane to the PSC substructure are reported in Fig. 3b. Even in this test, web and flange buckling revealed at the first hemicycle with a displacement ductility factor of 4 whilst at the third positive hemicycle weld beads between the beam bottom flange and the column fractured. Nevertheless, the arguments posed in favour of the FSC substructure render the PSC substructure behaviour quite admissible. In order to grasp the behaviour of the aforementioned substructures with respect to random variable amplitude displacements some pseudo-dynamic test results are commented upon. The reaction force-displacement responses corresponding to the N69W component of the 1952 Taft earthquake, applied with a peak ground acceleration of 2.0g are mirrored in Fig. 4a and 4b for FSC and PSC substructure, respectively. One can observe an acceptable behaviour of the specimens up to the interstorey drift limits. Soon after, local instability phenomena reduced the energy consumption characteristics of specimens. Moreover, the energy absorption properties of specimens under pull loading were not exploited.

1.2 Finite Element Model and Analyses

The three-dimensional (3D) finite element modelling of PSC beams poses several problems due in part to the lack of interface material properties as well as in part to general computational difficulties. Thereby, a 2D finite element model that retains the most significant facets of the actual composite substructure was conceived by Bursi and Gramola [4]. Such a model is represented in Fig. 5 and it includes the following characteristics, among others: (*i*) discrete connectors with finite head dimensions, in order to reproduce the actual compressive stress state in the concrete deck; (*ii*) discrete reinforcing steel bars; (*iii*) overlapped nodes in order to simulate both structural and reinforcing steel-concrete interfaces. In this on-going investigation, elastic-plastic plane-stress simulations are performed on the test substructures by means of the concrete constitutive models available in the ABAQUS code [5]. In these models, a macro-level approach is adopted for concrete fracture and the plain concrete is assumed to be an equivalent isotropic continuum with smeared cracks. Longitudinal steel reinforcements in the composite deck were considered made of an hardening elastic-plastic material and were modelled either as *discrete* two-noded truss elements or as *smeared* overlay on top of smeared-crack elements. In the case of *discrete* reinforcements, the yield criterion for concrete was assumed to be an elastic-plastic model with strain-hardening based on the Drucker-Prager yield surface with a non-associated flow rule. When *smeared* reinforcements were adopted, the rebar-concrete interaction in the tensile stress regime was modelled implicitly by appropriate modifications of the constitutive relations of concrete. In such conditions, a more sophisticated inelastic concrete model embodied in the ABAQUS code [5] was adopted. In order to reduce the analysis complexity, only monotonically increasing loading is considered. As a result, some low-cycle degrading phenomena are neglected and the monotonic responses are assumed to be the skeleton curves. Moreover, only comparisons among test data and analyses relative to the FSC substructure in the predominant compressive stress state (pull loading) are discussed. In order to capture friction effects between the structural steel (beam upper flange and stud connectors) and the concrete, two limiting cases are analysed: full slip (low friction) and full stick (high friction) conditions. Relevant results are reported in Fig. 6a and, as expected, local friction effects appear to be not so significant. Substructure performances are analysed when *discrete* reinforcing bars are embodied into the model, *i.e.* when the bond stress-slip relationships are taken into account. In addition, the full slip condition was considered whilst the stud shear connectors were replaced with horizontal discrete springs characterised by hardening elastic-plastic constitutive laws obtained via pull-push

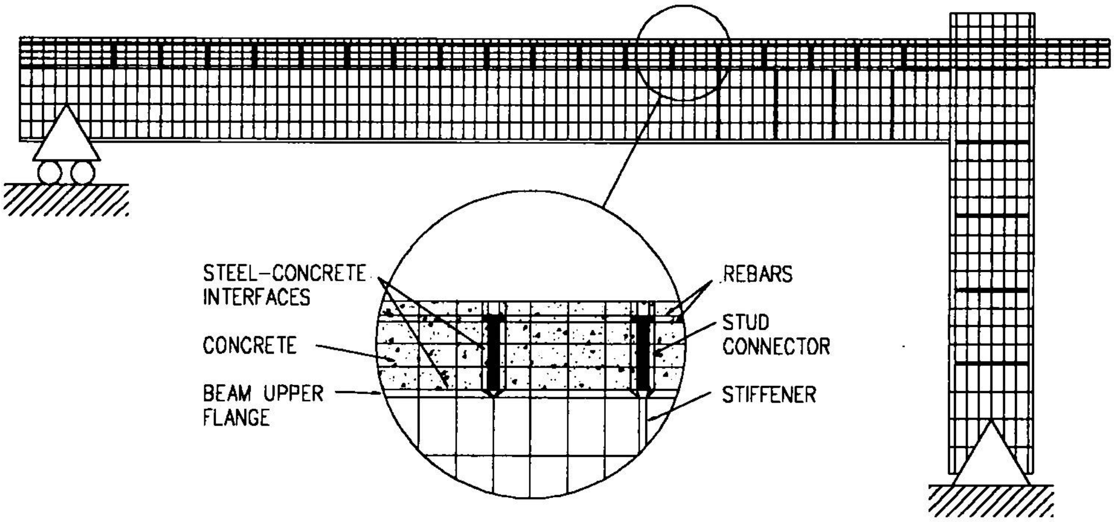

Fig. 5 Refined two-dimensional finite element model of substructure with full shear connection

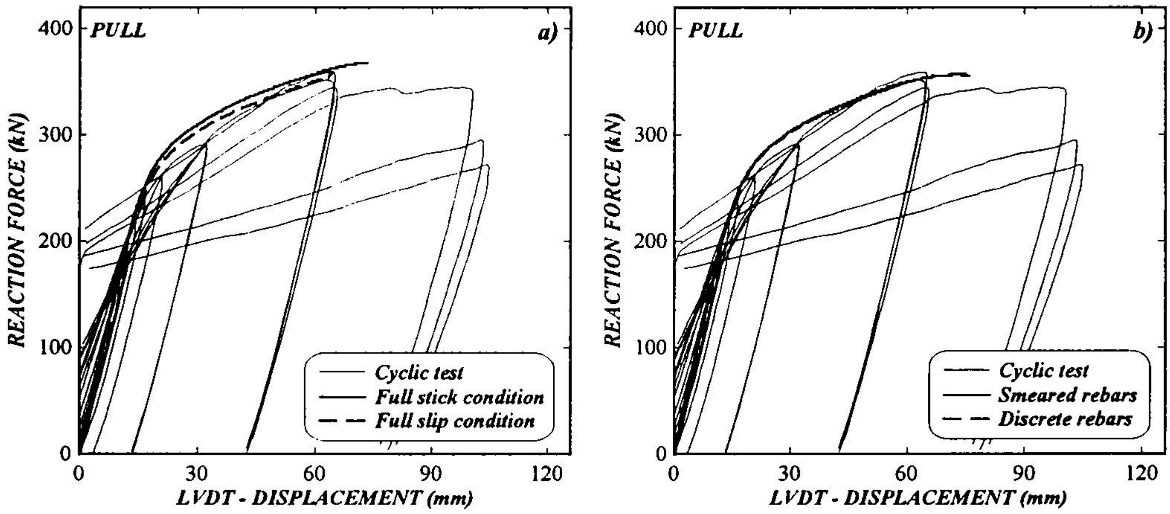

Fig. 6 Experimental and numerical results for full shear connection substructure: a) smeared rebars; b) non-linear spring connectors

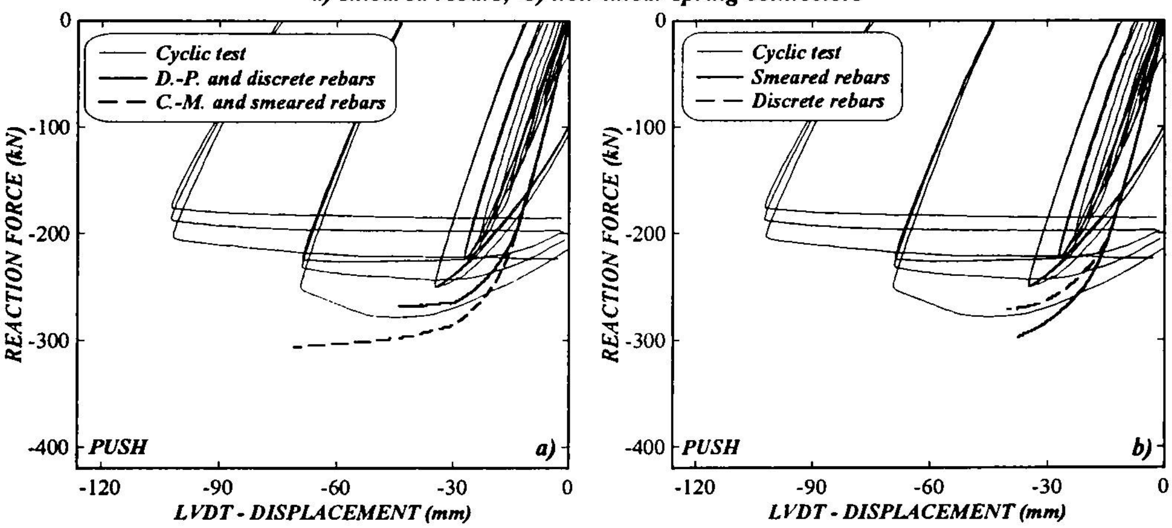

Fig. 7 Experimental and numerical results for full shear connection substructure: a) Drucker-Prager (D.-P.) and Concrete-Model (C.-M.); b) non-linear spring connectors

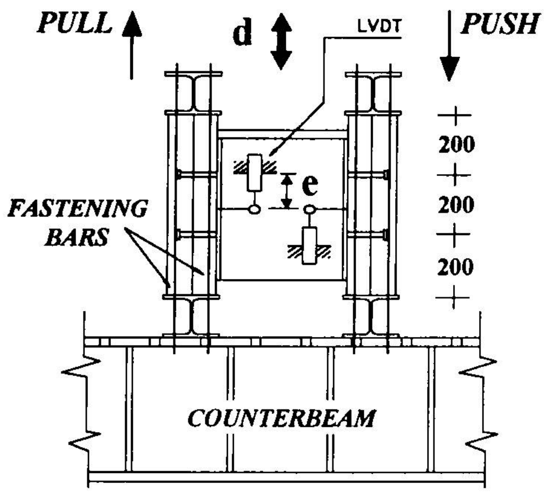

Fig. 8 Schematic lay-out of pull-push specimens

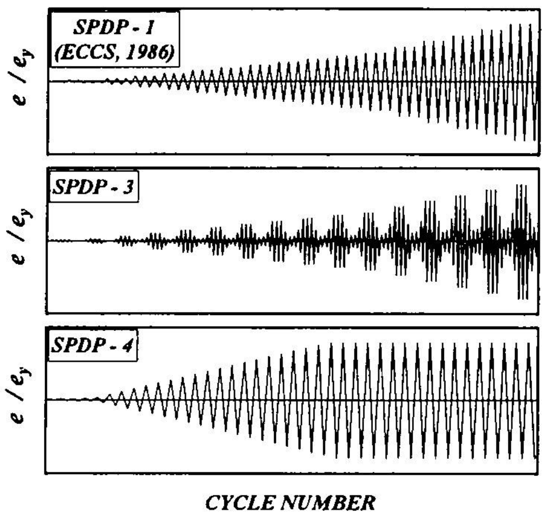

Fig. 9 Sequencial-phased displacement test procedures

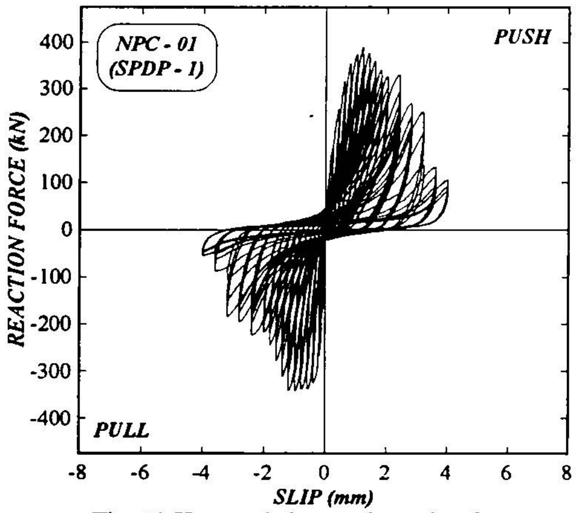

Fig. 10 Hysteresis loops of reaction force vs. controlled slip of specimen NPC-01

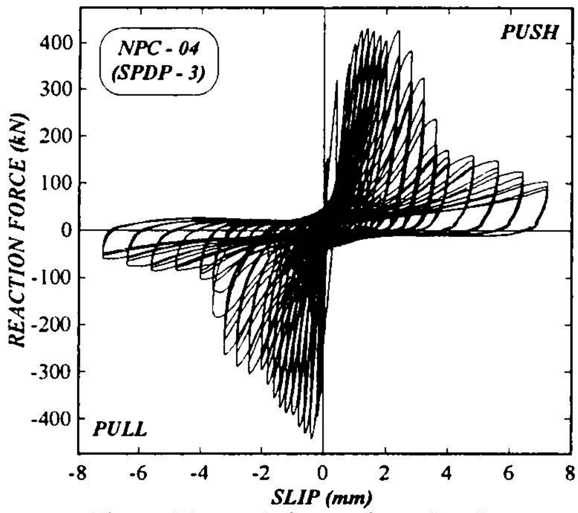

Fig. 11 Hysteresis loops of reaction force vs. controlled slip of specimen NPC-04

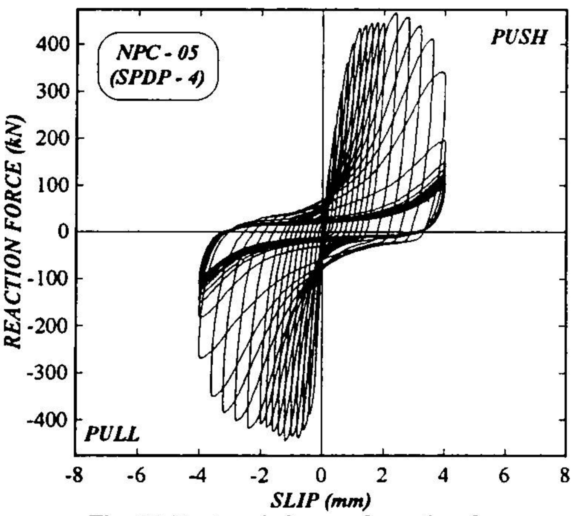

Fig. 12 Hysteresis loops of reaction force vs. controlled slip of specimen NPC-05

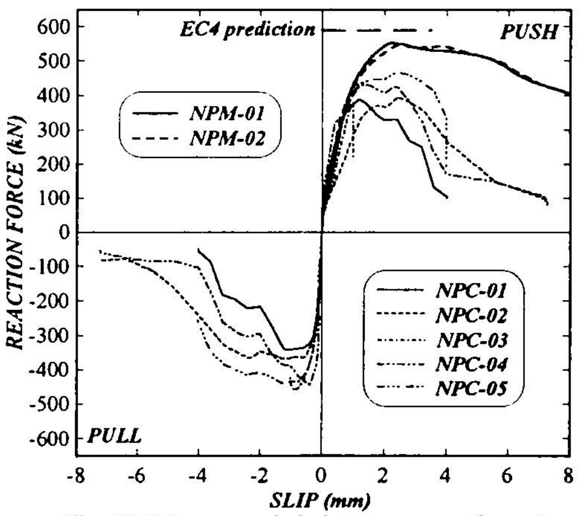

Fig. 13 Primary and skeleton curves of reaction force vs. controlled slip of pull-push specimens

tests [1]. In order to suppress uplift, scleronomic constraints were imposed between the beam upper flange and the concrete deck. As a matter of fact, the overall simulated response highlighted in Fig. 6b is affected slightly by the bond stress-slip behaviour, owing to the predominant deck compressive stress state. Moreover, the high shear connection degree ($N/N_f = 1.32$) mitigates the effects caused by the presence of discrete springs. Nevertheless, the simulated responses result less strong because the confining effect exerted by the stud connector heads is lost. In a similar fashion, analyses were repeated for the stress regime characterised by the deck in tension. In this context, the bond stress-slip relationships have a significant bearing on the substructure strength as mirrored in Fig. 7a and these effects appear to be independent from the shear connection degree [4]. A similar trend persists even though discrete springs reproduce the actual stud shear connector responses as mirrored clearly in the simulations plotted in Fig. 7b.

2. Pull-Push Specimens

In order to expand the experimental data base and to calibrate finite element models for concrete-stud connector interaction, eleven customary pull-push specimens were tested in two series. For brevity, only some results germane to the second test series are commented here. The geometrical characteristics of these specimens are identical to those of the composite beams whilst the test specimen and set-up are plotted in Fig. 8, schematically. The relative slip *e* depicted in the same figure was assumed to be the prime parameter of test control. Some of the displacement histories are summarised in Fig. 9. In detail, the displacement procedures comprise both variable and constant sequential-phased displacement histories to impose different cumulative damages on the specimens. The reaction force-slip response of the NPC-01 specimen is highlighted in Fig. 10. The observed inelastic behaviour is caused by stud connector yielding and concrete fracturing whilst the specimen collapse was governed by concrete crushing. The stiffness and strength degradation in the range of the maximum load is limited. The corresponding cyclic response of NPC-04 specimen is plotted in Fig. 11. One can observe an increase of both strength and ductility properties of the specimen. The hysteretic behaviour of the NPC-05 specimen is shown in Fig. 12. The specimen was able to develop large reaction forces at large displacement ductility factor as a consequence of the displacement procedure SPDP-4 characterised by only one cycle per variable amplitude. Finally, the primary load-slip relationships provided by two specimens tested in a monotonic regime as well as the skeleton curves of the other specimens are collected in Fig. 13. One can observe how reversed displacement cycles inflict to the specimen responses a reduction both of strength and ductility. The mean shear resistance predicted by EC-4 [2] without safety factors is depicted in the same figure. One can observe the unsafe prediction, specially owing to the detrimental effects of reversed displacements. The investigation of the low-cycle behaviour as well as the calibration of damage criteria for composite members deserve additional future studies.

Acknowledgements

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References

[1] Bursi O.S. and Ballerini M., "Behaviour of a Steel-Concrete Composite Substructure with Full and Partial Shear Connection", *Eleventh WCEE*, Acapulco, (1996), Paper No. 771.

[2] Eurocode 4 - ENV 1994-1-1:"Design of Composite Steel and Concrete Structures-Part 1-1: General Rules and Rules for Buildings", *European Committee for Standardisation* (1992)

[3] Technical Committee 13, "Recommended Testing Procedures for Assessing the Behaviour of Structural Steel Elements Under Cyclic Loads", *ECCS*, (1986), No. 45.

[4] Bursi O.S. and Gramola G., "Smeared Crack Analyses of Steel-Concrete Composite Substructures", *STESSA '97*, Kyoto, (1997).

[5] ABAQUS - User's Manual, ver. 5.5, Vol. 1-2, Hibbitt, Karlsson & Sorensen Inc., (1996).