



# Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost

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# Cyclic loadings on steel and lightweight concrete composite beams

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**ABSTRACT:** This communication describes the experimental cyclic tests performed on steel and high strength lightweight concrete composite beams, at Universidade do Minho, Portugal. The experimental study involves tests on simply supported beams, all with the same geometrical disposition, supports and materials. Headed studs are used to provide the connection between the steel profile and the lightweight concrete slab. The parameters in study are the stud disposition and the number and range of the load cycles applied. Two types of stud disposition are chosen: one that guarantees full connection and other that guarantees partial connection. The beams are tested with a six-point loading, uniformly spaced along the beam, and the cycles are controlled by load. The main objectives are: to describe the composite beams behaviour, focused on the connection between steel and lightweight concrete; to analyse the beams load capacity and to analyse the influence of the number and range of the load cycles.

## 1 INTRODUCTION

The use of steel and concrete composite structures accounts for the contribution of the two materials, provided that a composite action exists between steel and concrete members. Reducing or preventing the relative displacement of concrete and steel sections at their interface guarantees the composite action. Shear connectors are used to provide this composite action. Recent investigation proved that the use of shear studs is adequate when using high strength concrete Hegger et al. (2001). Good results were also obtained with high strength lightweight concrete in Push-out tests recently performed, Valente & Cruz (2004), Valente et al. (2005).

This communication describes the experimental tests on four simply supported steel and lightweight concrete composite beams with a 4.5 m span. The transversal section, span length and supporting conditions are identical for every beam. Shear connection elements distribution and load distribution are the varying parameters. Studs are used for shear connection and thus providing the composite action. The beams design puts particular emphasis on steel and lightweight concrete shear connection behaviour. In addition, the contribution of the different elements that constitute the beams on load and deformation capacity is analysed.

## 2 BEAMS IN STUDY

The beams are composed by an IPE120 steel profile and a 350 mm × 60 mm lightweight concrete slab (Figure1). Shear connection is provided with equally spaced shear studs of 13 mm diameter and 50 mm high. The shear connectors distribution is of two types: *Type 1* - total connection, with 8 studs of 13 mm diameter and 50 mm height, distributed in half span of the beam

and *Type 2* - partial connection with 4 studs of 13 mm diameter and 50 mm height, distributed in half span of the beam (Table 1).

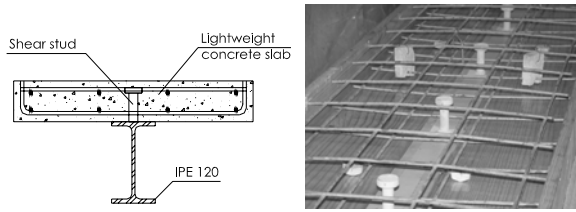


Figure 1. Beam cross section and formwork.

Table 1. Distribution of stud connectors.

Beam	Connection	Stud distribution
VM4	Total	<i>Type 1</i>
VM6	Partial	<i>Type 2</i>
VM9	Total	<i>Type 1</i>
VM10	Partial	<i>Type 2</i>

The load configuration considered corresponds to four concentrated loads, equally spaced of 900 mm along the beam, approximating a uniformly distributed loading (Figure 2).

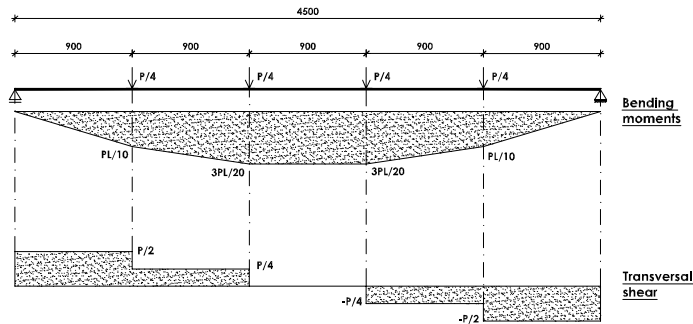
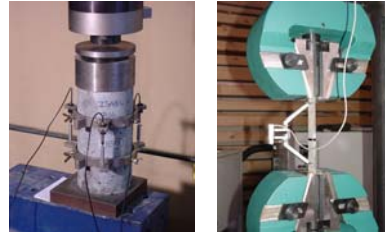


Figure 2. Loading and corresponding bending moment and shear force diagrams.

The values for the materials tested are presented in Table 2. The medium values presented for each property are the average result of three specimens' tests.

Table 2. Material properties.

Material ref.	Beam	$f_{cm}$ MPa	$E_{cm}$ GPa	$f_{ym}$ MPa	$f_{um}$ MPa
BL33	VM4	55.60	22.08	-	-
BL34	VM6	54.72	23.82	-	-
BL30	VM9	65.81	25.71	-	-
BL31	VM10	65.51	25.03	-	-
Steel profile	all	-	-	335.7	491.1



### 3 TEST PROGRAM AND PROCEDURES

Four composite beam specimens were tested, in order to evaluate the composite beams cyclic behavior. Of these four specimens, two are submitted to monotonic loading, for evaluation of the connection load-bearing capacity and the load-slip curve, and the other two are submitted to cyclic loading, with the characteristics presented in Table 2.

In general, all the tests are conducted in the following steps:

1. The system applies  $N$  cycles of load/unload between the extreme values of the load range.
2. If failure is not attained during the load cycles, the system applies a monotonic loading controlled by a slip rate of 0.02 mm/s until a total vertical deformation of 60 mm, measured at the beam mid span is completed (the control is done with transducer V2).
3. Following this, the system applies a monotonic loading controlled by the displacement of the actuator, with a rate of 0.05 mm/s, until failure of the specimen is attained.

Table 2. Experimental program for composite beams tests.

Beam	Connection	Loading type	Load range	Number of cycles
VM4	Total	Monotonic	3.8-17	25
VM6	Partial	Monotonic	3.8-17	25
VM9	Total	Cyclic	5-35	5000
VM10	Partial	Cyclic	5-30	11000

#### 4 TEST SETUP

As represented in Figure 3, the actuator load is divided into several identical smaller loads in order to establish the chosen loading configuration. The set up is represented in Figure 3 as well as the final test configuration, immediately before the test begins.

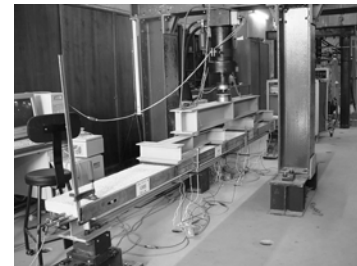
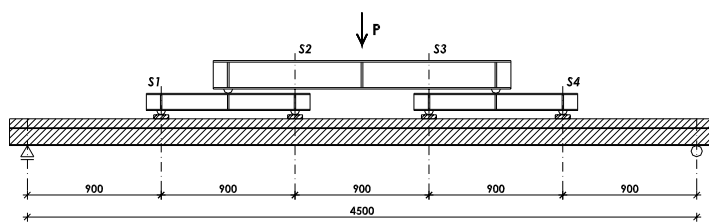
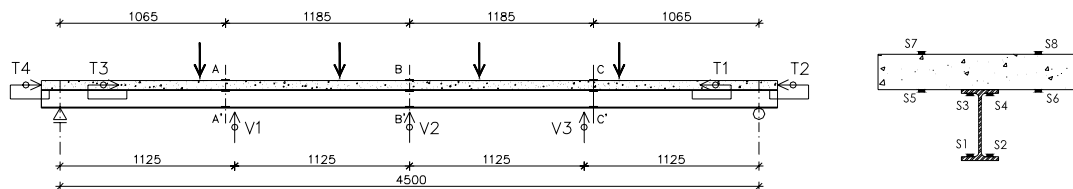


Figure 3. Test setup.

In order to establish critical sections for the beams, reference sections S1 to S6 are defined in Figure 4. Sections A-A', B-B' e C-C' from Figure 4 correspond to strain gauge location. Displacement transducers V1 to V3 measure the beam vertical deformation and displacement transducers T1 to T4 measure slip between the steel beam and the lightweight concrete slab. All of these measuring devices are represented in Figure 4.



a) Displacement transducers.

b) Strain gauge disposition (at cross sections A-A', B-B' and C-C').

Figure 4. Test monitoring.

#### 5 RESULTS FROM TESTS

##### 5.1 Failure modes

Beam VM4 shows a bending failure. Concrete crushes near the load application point at section S3 (see Figure 3). At the same time, concrete smashing initiates in the upper fibre, near position S2. This occurs while a longitudinal crack at the concrete section mid height grows towards the beam mid span (Figure 5). Different from the previous beam, VM6 suffers shear connection failure between the concrete slab and the steel beam. Connector failures are phased, with load capacity losses associated. This failure happens essentially in one side of the beam and vertical separation between the steel beam and the concrete slab is visible (Figure 6), near the beam supports.



Figure 5. VM4 failure.



Figure 6. VM6 failure.

The load range cycles applied to beams VM9 and VM10 were of smaller magnitude than the maximum load applied to beams VM4 and VM6. As Beam VM9 did not suffer failure during the load cycles, a monotonic loading was applied, until failure was attained. The result was that beam VM9 suffered bending failure (Figure 7). The 11000 load cycles applied to beam VM10 were not enough to provoke failure and therefore a monotonic loading was also applied to this beam after the load cycles. Beam VM10 suffered shear connection failure.



Figure 7. VM9 failure.



Figure 8. VM10 failure.

## 5.2 Load capacity

According to EN1994-1-1 (1994), bending failure is considered for beams with total connection design. At failure, the total plastic behaviour of the cross section is accepted, as it is classified on class 1. In the case of partial connection beam design, shear connection failure is admitted, resulting in an inferior value for the maximum bending moment. Predicted values for maximum sagging bending moment ( $M_{pl,R}^+$ ) are presented in Table 3 (the effect of cyclic loading is not considered).

Load and corresponding ultimate bending moment values can be predicted with an ultimate limit state analysis. The material properties needed for that analysis are presented in Table 2. The values of maximum sagging bending moment were determined considering always the maximum strain of 3.5 mm/m on the concrete slab. For monotonic loadings, the stud failure is calculated according to equation (1), considering the value of 500 MPa for steel ultimate tensile strength of the connector,

$$P_R = 0.8 f_u (\pi d^2 / 4) \quad (1)$$

where  $d$  is the stud diameter.

Table 3. Predicted maximum bending moments for monotonic loading.

Concrete Reference	Beam	$F_{cf}$ (kN)	$F_{af}$ (kN)	$M_{pl,R}^+$ (kNm)	$P_{max}$ (kN)
BL33	VM4	992.5	443.5	47.3	70.0
BL34	VM6	976.8	443.5	37.3	55.3
BL30	VM9	1174.7	443.5	48.2	71.4
BL31	VM10	1169.4	443.5	37.6	55.7

$F_{cf}$  – maximum compressive force to be mobilized at the concrete section ( $F_{cf} = 0.85 \times f_{cm} \times A_c$ )

$F_{af}$  – maximum tensile force to be mobilized at the steel section ( $F_{af} = f_{ym} \times A_a$ )

The experimental values of maximum sagging bending moment and maximum applied load are presented in Table 4.

Table 4. Maximum bending moment and corresponding applied load.

Concrete Reference	Beam	Failure type	$P_{max}$ (kN)	$M_{max}$ (kNm)	$V_{max}$ (kN)
BL33	VM4	Bending	77.92	52.60	38.96
BL34	VM6	Shear connection	62.16	41.96	31.08
BL30	VM9	Bending	78.32	52.86	39.16
BL31	VM10	Shear connection	38.08	25.70	19.04

The maximum load applied to beams VM4 and VM9 (see Table 4) are similar and exceed the maximum load predicted in Table 3. The maximum load applied to beam VM6 also exceeds the maximum load predicted, meaning that the shear connection may present higher load capacity than considered. Beam VM10 is affected by the load cycles applied, resulting in a maximum bending moment that is inferior than predicted.

Both beams designed for total connection (VM4 and VM9) suffered bending failure. The average load range value effectively applied to beam VM9 by the hydraulic system is equal to 35.93 kN and the average maximum load applied is equal to 39.46 kN. This maximum load corresponds to 50.6% of the maximum load applied to beam VM4. Elastic behaviour of the composite beam is expected for this load value, which can be concluded from the results obtained on beam VM4. The maximum load applied is almost identical for the two beams, which shows that there is no load capacity loss resulting from the 5000 load cycles applied to beam VM9.

Both beams designed for partial connection (VM6 and VM10) suffered shear connection failure. The average load range value effectively applied to beam VM10 by the hydraulic system is equal to 28.97 kN and the average maximum load applied is equal to 32.78 kN. This maximum load corresponds to 52.7% of the maximum load applied to beam VM6. Elastic behaviour of the composite beam is expected for this load value, which can be concluded from the results obtained on beam VM6. However, unlike it occurred for the beams with total connection design, the maximum load applied to beam VM10 is considerably smaller than the maximum load applied to beam VM6, which shows that there is load capacity loss resulting from the 11000 load cycles applied to beam VM10.

The comparison established between these two pairs of composite beams puts in evidence that a composite beam designed for partial connection is more affected by cyclic loading than a composite beam designed for total connection.

### 5.3 Evolution of slip

Figure 9 shows the slip values for VM4 and VM6. On beam VM4, initially both transducers measure similar values of slip. On the final phase of the test, T2 measures values that are higher than T4 and failure initiates at section S3, positioned on the same half side of the beam. The slip values measured for VM6 are much higher than the values measured for VM4. Slip at VM6 grows particularly on one side of the beam (measured by T4). In the test initial phase, the slip evolution measured by both transducers is very similar. Following the failure of the first connector, the slip growth concentrates on one side of the beam ending with the progressive failure of all the studs localized at this half.

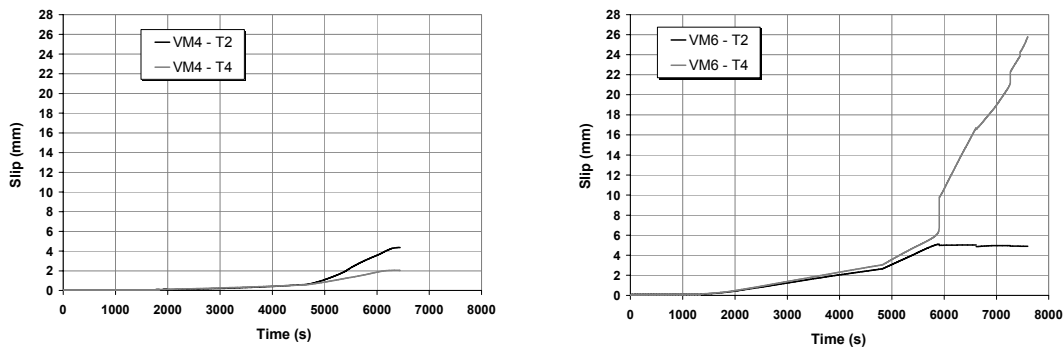


Figure 9. Slip for beams VM4 and VM6.

Figure 10 shows the evolution of maximum slip during the load cycles applied to VM9. The level of load applied is in a range that fits the elastic behavior of the shear connection. Even so, during the 5000 cycles of a constant load range applied to beam VM9, it is possible to identify that slip grows with the number of load cycles applied and that this growth is approximately linear. The linear growth rate is equal to  $4.33 \times 10^{-6}$  mm / cycle.

Within this experimental work, some push-out tests were performed with the same stud dimensions and the same type of lightweight concrete as were used on the beams' tests. If the rate of slip growth measured for beam VM9 is compared to the values of slip growth measured during the cyclic push-out tests, two facts are observed:

- the configuration of the maximum slip vs. number of load cycles is well approximated by a linear law as was previously observed during the push-out tests;
- the value of slip growth obtained in the beams' tests is smaller than any of the growth rates measured during the cyclic push-out tests, although it is close to the value obtained for one of the tested push-out specimens, with similar  $\Delta P/P_{max}$ .

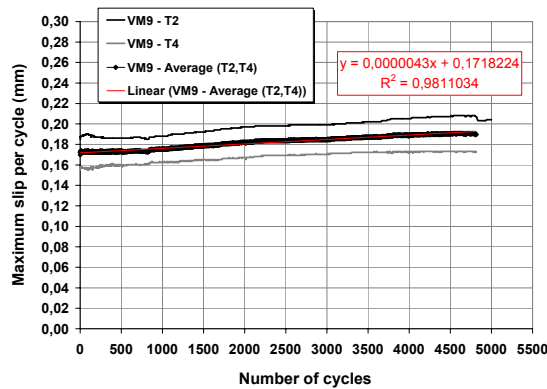
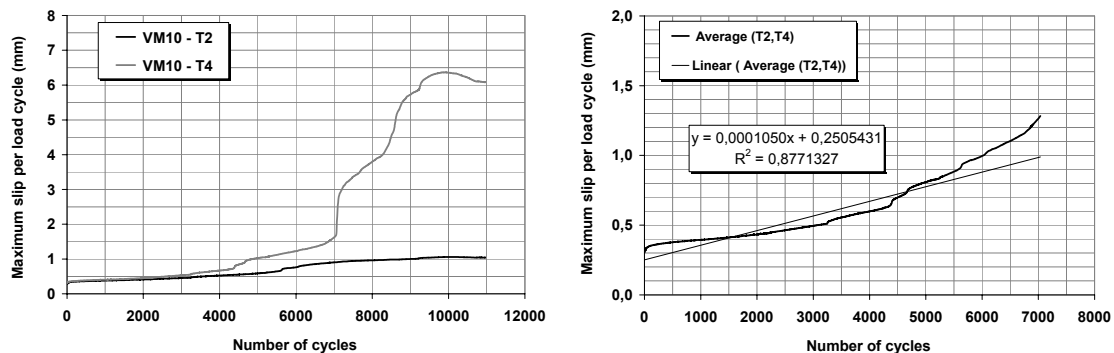


Figure 10. Evolution of slip during the load cycles applied to VM9

Figure 11 shows the evolution of maximum slip during the load cycles applied to VM10. The rate of slip growth is approximately the same for the first 4500 load cycles. After these cycles, it suffers a small increase until around 7000 cycles are completed. From this moment on, large slip values develop on one side of the beam, while the other side tends to maintain the slip previously achieved. The rate of slip growth until  $N = 7000$  cycles is well approximated by a linear law. This linear growth rate is equal to  $105.0 \times 10^{-6}$  mm / cycle.



a) Complete curve ( $N_{cycles} = 11000$ )      b) Initial part of the curve ( $N_{cycles} = 7000$ )  
Figure 11. Evolution of slip during the load cycles applied to VM10

#### 5.4 Evolution of strain during the load cycles

Figure 12 illustrates the strain diagrams for beams VM4 and VM6 mid span cross sections. The strain diagrams correspond to 40%, 90% and 100% of the maximum measured bending moment. For the lowest level of loading,  $0.4M_{max}$ , the strain distribution is uniform, with total compatibility between both materials. The steel to concrete connection guarantees the total shear



force transmission for  $0.4M_{max}$ , even for beams with partial connection design. The total interaction hypothesis is valid for VM4 even for maximum bending moment. For VM6, the loss of shear connection is verified from lower loads.

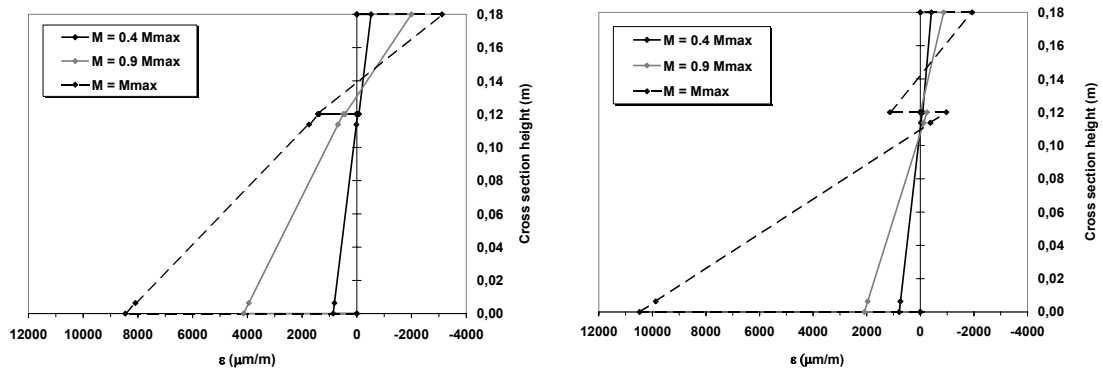
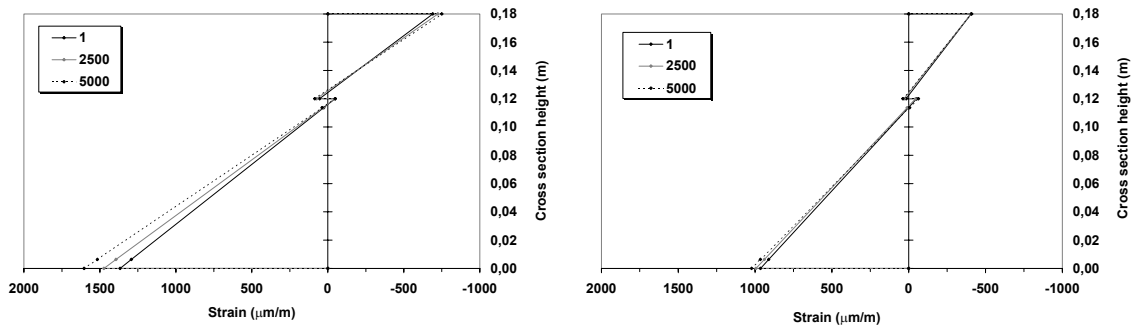


Figure 12. Strain diagram for VM4 (left) and VM6 (right)

Figure 13 presents the strain diagrams in two cross sections of beam VM9: B-B' (midspan) and C-C' (quarter span) (see Figure 4). Beam VM9 was designed to have total connection at the interface between steel and concrete sections.

There is little variation on the strain diagram during the load cycles application. In both cross sections, the variation of slip,  $ds/dx$ , suffers a small increase during the 5000 load cycles applied, which means that the evolution of slip presented in Figure 12 has a small influence on the beam behaviour. During the 5000 load cycles applied, a curvature increase of approximately 14% is verified, according to the strain measurements done.

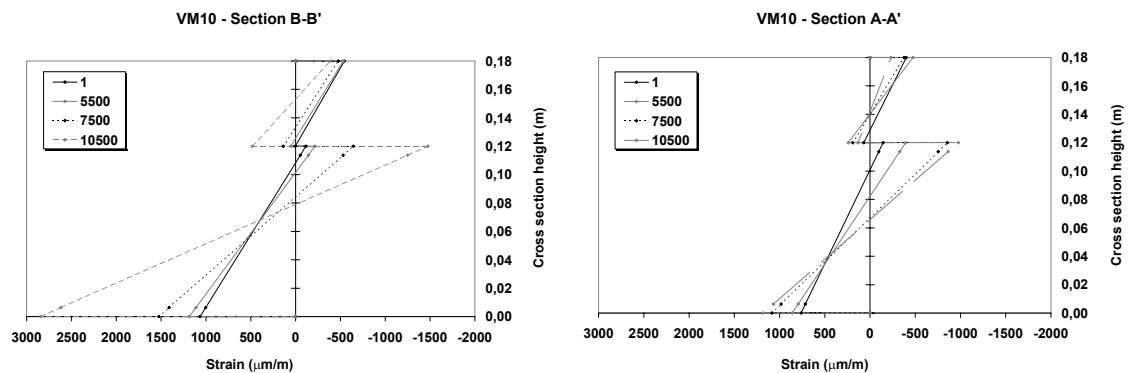


a) Beam VM9 – Mid span

b) Beam VM9 – Quarter span

Figure 13. Evolution of strain during the load cycles applied to VM9

Figure 14 presents the strain diagrams in two cross sections of beam VM10: B-B' (mid span) and A-A' (quarter span). Beam VM10 was designed to have only partial connection at the interface between steel and concrete sections.



a) Beam VM10 – Mid span

b) Beam VM10 – Quarter span

Figure 14. Evolution of strain during the load cycles applied to VM10

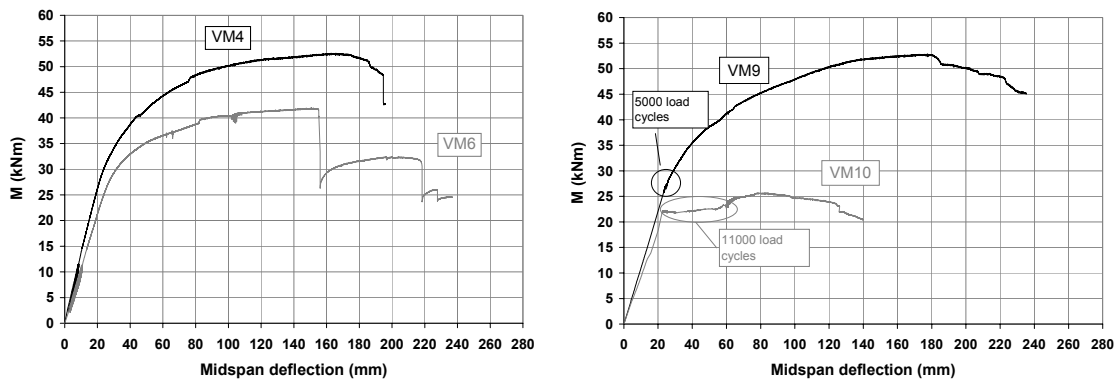
In this case, the strain diagrams presented show high variation during the load cycle application. There is an important increase on the variation of slip,  $ds/dx$ , during the 11000 load cycles applied, resulting in an important transfer of stress between the concrete and the steel sections.

At section B-B', maximum strain at the steel section grows to more than twice its initial value, while maximum strain at the top fiber of the lightweight concrete section tends to decrease as there is loss on the steel to concrete connection.

### 5.5 Evolution of vertical deflection

Figure 15 presents the experimental bending moment vs. vertical deformation diagram, measured at the beams' mid span. Beams VM4 and VM6 show an initial elastic behaviour, approximate to the estimated by an elastic approach. Considering the elastic zone for both types of loading, the total connection hypothesis (VM4) show higher stiffness. A loss of stiffness is verified at each specimen for values over  $0.45 M_{max}$ . Before failure, beam VM6 presents higher vertical deformation than beam VM4, when comparing the same level of loading.

The diagram correspondent to beam VM9 is very similar to the diagram presented for beam VM4, which means that the 5000 load cycles could not induce a significant increase of deformation. On the opposite, an increase on the vertical deformation is observable for beam VM10 during the 11000 load cycles applied, leading to an early failure of the beam.



a) Beams VM4 and VM6

b) Beams VM9 and VM10

Figure 15. Maximum bending moment vs. vertical deformation (at beam mid span) – all beams

## 6 CONCLUSIONS

Beams VM4 and VM9 suffered bending failure and beams VM6 and VM10 suffered shear connection failure, as predicted. Beams VM9 and VM10 were submitted to cyclic loads. The load levels and number of cycles applied induced reduced loss of shear connection on beam VM9, while for beam VM10, the loss of shear connection resulted in a reduced maximum resistant bending moment.

## 7 REFERENCES

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