REVIEW OF AUSTRALIAN SUPPORT-SETTLEMENT TESTS ON CONTINUOUS, ONE-WAY REINFORCED-CONCRETE SLABS INCORPORATING LOW-DUCTILITY REINFORCEMENT

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ABSTRACT

Without movement joints present, differential vertical settlement or displacement of permanent members such as walls, columns or beams supporting continuous concrete slabs can increase the ductility demand on critical regions. This is due to additional amounts of moment redistribution, which might be overlooked or ignored in normal structural design practice. Over the past six years, independent test series have been undertaken at three Australian universities to primarily examine the detrimental effect support settlement could have on the load-carrying capacity of continuous one-way reinforced-concrete slabs incorporating low ductility (Class L) welded mesh. All peak moment regions of the slabs were under-reinforced, and tensile fracture of main bars ultimately occurred. Despite inducing a large amount of moment redistribution by imposing significant differential support settlement before loading a slab to failure, this had little effect on load-carrying capacity. This capacity was estimated either analytically or preferably from a test on a companion slab tested in its original position without support settlement. Aspects of the three independent tests series are briefly described. When designing statically indeterminate members incorporating Class L mesh for strength to Australian Concrete Structures Standard AS 3600–2009, engineers have various options available to them that include redistributing elastically-determined peak bending moments provided analysis (or testing) shows that the rotation capacity of critical moment regions is compatible with the design assumptions. The design of a double-span slab for support settlement is considered using the results of two tests performed at Curtin University of Technology for the SRIA.

INTRODUCTION

Concern has been raised in Australia about using Class L mesh as main reinforcing steel in indeterminate beams and slabs supported either directly or indirectly on foundations that can experience relative vertical movements during the life of a structure, for simplicity referred to as ‘support settlement’ herein. Support settlement has the potential to cause significant redistribution of bending moments and increased flexural cracking, and can therefore change the ductility demand placed on critical sections in bending, and alter the final collapse mechanism, overall deflection and ultimate load.

Clause 7.6.8.3 of AS 3600–2001 (SA 2001) required engineers to account for the effects of support settlement when elastically designing beams or slabs incorporating Class L mesh as main reinforcement. This requirement no longer exists in AS 3600–2009 (SA 2009). However, overarching Clause 1.1.2(d) requires that Class L mesh “*shall not be used in any situation where the reinforcement is required to undergo large plastic deformation under strength limit state conditions*”. Elastic design without redistribution (Patrick et al. 2005) does not depend on plastic deformation, so is an acceptable general design approach, & its application to a support settlement case will be examined below.

Three independent series of support-settlement tests have now been completed at three Australian Universities, viz. University of Melbourne, University of New South Wales (UNSW) and Curtin University of Technology (CUT). While results of the University of Melbourne and UNSW test series have been studied in some detail by their respective researchers, the Australian test results have yet to be studied collectively. With the imminent release of the CUT test results (Chandler and Lloyd 2010) this will be the subject of future papers. The three test series are briefly described below.

Several of the university researchers have used finite element analysis to model the complex behaviour of their test slabs, including support settlement. Advanced models based on test results could be used to develop simple practical design methods.

DEFINITION OF AMOUNT OF MOMENT REDISTRIBUTION, β

The amount of moment redistribution, β, that occurs at a critical section under peak moment is defined herein as the percentage difference between the bending moment (M^* or M) and that calculated ignoring redistribution (M_e^* or M_e), according to the following applicable formulae (note: negative redistribution occurs if the value of M^* or M is less than that of M_e^* or M_e, respectively, such that $0 < (M^*/M_e^*$ or $M/M_e) < 1$):

- for design using AS 3600–2009: $\beta = -100(1 - M^*/M_e^*)$, where M^* is the design bending moment and M_e^* the elastically-determined design bending moment before moment redistribution, under the same design actions; or
- during a test: $\beta = -100(1 - M/M_e)$, where M is the actual bending moment and M_e the elastically-determined bending moment before moment redistribution, under the same applied actions.

PREVIOUS AUSTRALIAN SUPPORT SETTLEMENT TESTS

University of Melbourne

The University of Melbourne tests are reported by Siddique (2005), Siddique et al. (2005a, 2005b) and Goldsworthy et al. (2009), and have been partially reviewed by Patrick (2005), Keith et al. (2007) and Patrick and Keith (2008). There appear to have been problems with the tests, as the researchers seem to have lost track of the exact location of concrete-block kentledge they added while loading the slabs to failure. The slabs were stronger than they expected, so it became difficult to find room to place the blocks. Therefore, different scenarios need to be considered with regard to the amount of moment redistribution that occurred during the tests. This error also affects the degree to which a full plastic mechanism was developed. It could well be possible that the support settlement had no detrimental effect on the load-carrying capacity of each slab tested, i.e. close to a full plastic hinge mechanism might have formed in both tests.

University of New South Wales (UNSW)

More recently, Sakka and Gilbert (2008a) and Gilbert and Sakka (2009) reported the results of their own tests. Gilbert (2006) had previously undertaken elementary elastic analysis for a hypothetical design example involving a slab tested with rigid supports. He estimated the possible effects of support settlement, similar to how a design engineer might approach this without using more powerful analytical tools. Gilbert concluded that "*Evidently, a (modest) support settlement can cause a significant loss of strength for a continuous slab containing low-ductility reinforcement. In fact, any significant change in the distribution of internal actions from that assumed in design can reduce the strength of a continuous slab containing low ductility reinforcement.*" However, his conclusion was based on a simplistic assumption concerning "*the level of cracking in the slab*" to estimate the average flexural stiffness of the entire slab while the central support of the two-span slab was lowered, and also, in particular, any further redistribution of bending moments was completely ignored.

From their subsequent testing, Sakka and Gilbert (2008a) concluded that:

> "*A series of full range load tests is described on two-span continuous one-way reinforced concrete slabs containing Class L welded wire fabric (WWF). Five specimens were tested to investigate the impact of support settlement on ultimate strength. The results of the tests are presented and evaluated, with particular emphasis on the strength and failure mode of the slabs. All test slabs failed in flexure in a brittle and sudden manner by fracture of the tensile reinforcement with little plastic deformation and little prior warning of failure. The test slabs experienced high localized strain due to the high bond stresses that can develop locally adjacent to the critical crack due to the combined effect of the deformations on the small diameter wires and the anchorage provided by the welded cross wires in the WWF. However, the imposed support settlements did not affect the strength of the slabs and the reinforcement was able to accommodate the settlements without compromising the strength.*"

Nevertheless, Sakka and Gilbert (2008a) went on to conclude that:

> "*The WWF used in the experiments had a uniform elongation* ε_{su} *typically in excess of 3.4% and a strength-to-yield stress ratio* (f_{su}/f_{sy}) *in excess of 1.05. These values are significantly greater than the minimum limits for* ε_{su} *and* f_{su}/f_{sy} *specified for Class L reinforcement in the Australian Standard AS3600-2001; namely 1.5% and 1.03, respectively. Therefore, the observations concerning the effect of support settlement on the strength of the one-way slabs may not be applicable for Class L reinforcement that just satisfies these minimum limits.*"

This led them to develop a numerical model to predict the behaviour of slabs like they tested, but incorporating Class L steel with the lowest permissible ductility according to AS/NZS 4671–2001 (SA & SNZ 2001). Sakka and Gilbert (2008b) conclude that "*when* *zero moment redistribution is used in design, and when (uniform strain) ε_{su}<2.5%, a support settlement of about span/100 may reduce the strength by over 20%".*

SRIA SUPPORT SETTLEMENT TESTS PERFORMED AT CUT

The SRIA commissioned the CUT test series conducted using a special tubular steel ringbeam as a universal test rig to study the behaviour of three different arrangements: single-span one-way (SSOW); double-span one-way (DSOW); and two-way (TW). The load-deflection curves from two DSOW tests are shown in Fig. 1: slabs ST3 and ST4 were nominally identical with continuous top SL102 and bottom SL92 meshes. They were tested following the same detailed procedure (CUT & SRIA 2009) with roller end supports, except slab ST4 experienced an upward middle support movement of 5 mm (span/459) prior to being tested to failure. Overall slab depth was 110 mm with 20 mm cover, concrete compressive strength was 42 MPa, and centre-to-centre span 2295 mm.

The slabs were designed in accordance with AS 3600–2009 (CUT & SRIA 2010), ignoring any effects of the support settlement in the case of slab ST4. This gave rise to a design live load, Q=7.3 kPa, with negative bending strength governing and ϕ=0.64. As shown in Fig. 1, the design ultimate applied load per span correspondingly equalled 26.4 kN. In both tests, the maximum applied udl on each span reached just over 90 kN before some top or bottom main bars necked, then fractured as described in Fig. 1.

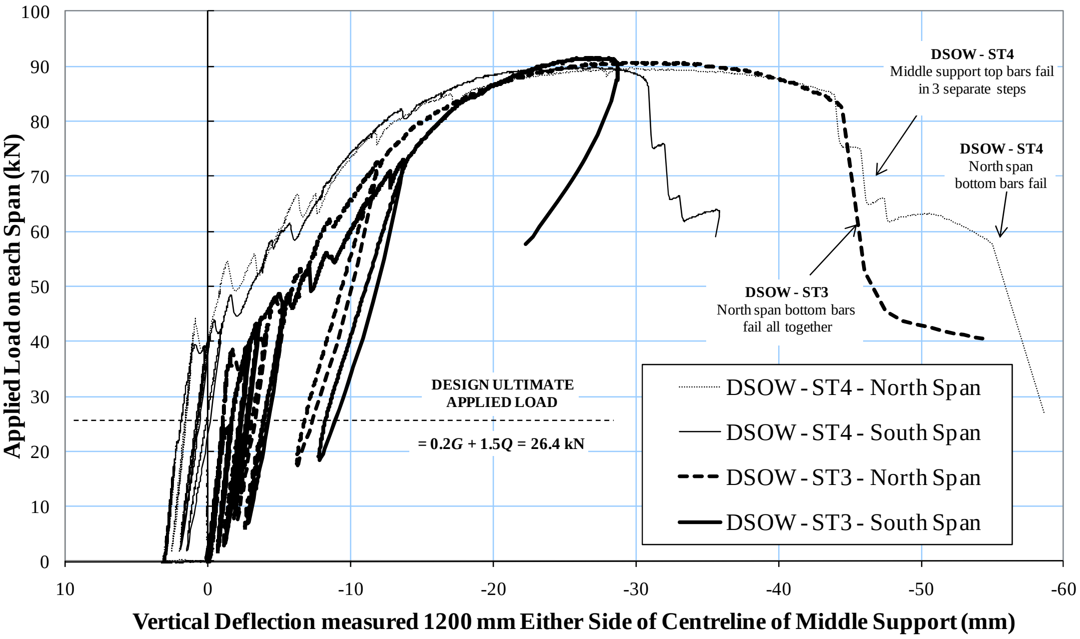

Fig.1: Load-deflection curves for CUT tests DSOW-ST3 and DSOW-ST4 (1m wide).

DISCUSSION & CONCLUSIONS

Although the CUT slabs were designed assuming β=0, large moment redistribution was exhibited at all stages of loading, e.g. at peak load, for slab ST3 almost -20% and +10% at the critical sections in negative and positive bending, respectively. Moreover, for slab ST4, in design and assuming an uncracked section, the 5 mm upward movement alone fully consumed the design negative moment capacity, so without redistribution there would be no reserve strength to accommodate any imposed load, making the design infeasible. Fig. 1 shows this would be grossly conservative for the conditions tested.

Patrick (2005) has suggested, that when designing slabs incorporating Class L mesh, to not separately account for the effects of possible support settlement unless they are considered likely to be at least ±span/250 at ultimate load, and to use $\phi=0.64$. Foster and Kilpatrick (2008a,b) have drawn a similar conclusion using an idealised tension-chord model, i.e. that "*the penalty (of 20% on ϕ) is sufficient to meet moment redistribution and support settlement demands*". SRIA (2008) gives the same advice. The results in Fig. 1 are consistent with this recommendation, but the CUT tests did not investigate downward movement of the central support, and the upward movement was only about half of span/250, as the design ultimate moment capacity was already fully consumed. Also, similar to the UNSW tests, the SL102 and SL92 meshes used in the CUT DSOW tests were not specially sourced and came from a normal supplier, and therefore their mechanical properties were typical of real production and significantly greater than the minimum requirements of AS/NZS 4671. The uniform strain of the SL102 and SL92 main bars used in the DSOW tests was on average about 3 % for both sizes, just above the 2.5% limit set by Sakka and Gilbert (2009b) but for settlements up to span/100.

Nevertheless, based on the three independent test series described in this paper, it appears that the potentially detrimental effects of support settlement in this form of construction are significantly less than first envisaged based on simple design principles using elastic analysis ignoring moment redistribution. SRIA's research into the behaviour of one-way and two-way slabs incorporating Class L mesh is continuing, and the CUT results will represent a significant contribution to the national test database.

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Scott Munter is a structural engineer and Executive Director for the Steel Reinforcement Institute of Australia (SRIA). Previously Scott worked for BlueScope Steel for almost 3 years as the Lysaght National Structural Decking Manager then High-Rise Business & Engineering Manager for BlueScope Buildings.

Scott served for 7 years with Australian Steel Institute as the State Manager-NSW then National Engineering Construction Manager working on a variety of key projects such as the Steel Connection Design Series. Scott also has a broad 15 year commercial, industrial and residential track record as a Civil & Structural Consulting Engineer with SCP Consulting in the Engineering Design and Construction field.

He graduated with a Bachelor of Structural Engineering (under the part-time attendance program, 6 year degree) from the University of Technology, Sydney in 1991 with 1st Class Honours, University Medal and the Engineers Australia Medal. As a Member of Engineers Australia he holds Charter Professional Engineer & NPER (Structural) status. He is a member of a number of Standards Australia committees including BD-002 Concrete Structures.

Mark Patrick holds BE and MEngSc degrees from Melbourne University and a PhD from Sydney University. For 6 years he was a consulting structural engineer; researched composite and concrete construction at BHP Melbourne Research Laboratories for 15 years; held a professorial position at the University of Western Sydney for 5 years; before starting a specialist structural engineering consultancy practice six years ago. He is a member of several Standards Australia committees including BD-002 Concrete Structures.