SHEAR RESEARCH NEEDS FOR ORDINARY CONCRETE BEAMS

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ABSTRACT

All concrete cross-sections need to be designed for bending-moment and for shear-force. Ultimate limit state calculations for bending-strength have not basically changed in the 70 years since Charles Whitney, Consulting Engineer of New York, suggested an elasto-plastic 'plane-section' hinge with a rectangular concrete stress-block. Most bending failures are quite ductile excepting some design error. Shear failures, on the other hand, vary from somewhat brittle to very brittle and design for shear has always been empirical.

Bending- and shear-failures both fall into the general category of 'in-plane' or 'plane-stress' problems. The state-of-the-art for plane-stress problems lags behind other areas of structural plasticity with the result that few 'exact' yield-line collapse mechanisms are well and widely known and understood. The outcome is that:

- Design of concrete for shear is still empirical in Australia/New Zealand/USA although …
- Eurocode 2 now allows a 'variable-angle strut' theory and …
- The draft of AS3600:2009 allows the 'strut-and-tie' method …
- The last two being variations on 'solely lower bound equilibrium solutions'.

For any given plane-stress problem, the use of some arbitrary lower-bound equilibrium solutions is better than no theory at all. The use of these equilibrium solutions is, nevertheless, a work-around for problems where the unique 'exact' yield-line collapse-mechanism is not yet well and widely known and understood. This author has progressed the theoretical study of 'exact' yield-line collapse mechanisms in ordinary concrete beams to include cases involving:

- Yield only of the longitudinal reinforcement for bending mechanisms and
- Yield of both the longitudinal reinforcement and the transverse shear reinforcement for combined bending-shear mechanisms.

The second group permits assessment of the shear reinforcement required to force a bending failure. To the best of his knowledge, these yield-line collapse mechanisms have only been published in his own writings. For any given problem:

- There will be an infinity of lower-bound equilibrium solutions, all of which are 'safe'.
- There is just one unique 'exact' yield-line solution.
- The 'exact' solution can always be repackaged as the optimum 'strut-and-tie' or 'variable-angle strut' solution.
- There will be a range of 'exact' yield-line collapse-mechanisms, each one of which will be 'exact' for some definite range of given problems.

There are now explicit needs for laboratory research. This author believes that laboratory research:

- Will demonstrate systematic improved performance for support bending ('dogleg') hinges as compared to mid-span (Whitney) 'plane-section' hinges and …
- Is necessary in order to complete understanding of the elasto-plastic effects of shear on the bending-strength of support hinges and to ensure that the 'strut-and-tie' method and the 'variable-angle strut' theory are, indeed, 'safe'.

The author now seeks collaborators. As a retired structural designer, he has no significant laboratory experience so his contribution would largely involve theoretical aspects similar to those herein. He thinks that this work may have an effect, say on AS3600: 2012 or later and he looks forward to that.

RE-INTERPRETATION OF AEES07 PAPER

Figs 9 and 12 are copied from the author's AEES07 Wollongong paper *Core Coupling-Beams in Tall Buildings*. That paper contains other 'exact' yield-line mechanisms which are specific to core coupling-beams, say L/D < 4. However Figures 9 and 12 illustrate collapse mechanisms which, with a little tweaking, are sufficient to provide 'exact' mechanisms for the full gamut of ordinary beams, say 4 < L/D < 25.

Core coupling-beams typically span door-openings in cores and so they usually have a clear-span of about one metre. It is then reasonable to focus on the earthquake/wind performance of coupling-beams neglecting gravity load. The AEES07 paper did that.

For longer spans, gravity load must be included and the tweaking required follows from that. With gravity included, the left/right skew-symmetry, shown in Figs 9 and 12, will be lost.

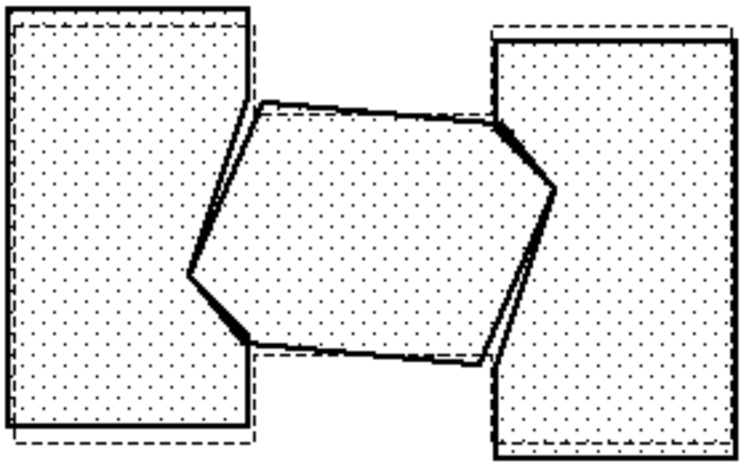

Fig 9: 'Dogleg' bending mechanism: displaced shape

- Fig 9 shows opposed 'dogleg' hinges at each end with no mid-span hinges. The dogleg hinges provide a load-path for shear onto the support. Modified to account for the loss of skew-symmetry, this is the appropriate 'exact' collapse-mechanism for load-cases involving bending-yield of earthquake-dominated beams where shear-failure is prevented.
- The load-case of full-gravity load (no earthquake or wind) requires three hinges:
    - one mid-span hinge will be the familiar (Whitney) 'plane-section' hinge and
    - tension-top dogleg hinges at both supports.
- Finally earthquake on gravity-load dominated beams will result in an offset mid-span (Whitney) 'plane-section' hinge with a support tension-top dogleg hinge at the down-earthquake (or down-wind) support only.

Thus, for ductile beams with shear-failure definitely prevented, all failures consist of combinations of mid-span 'plane-section' hinges with support 'dogleg' hinges. The mechanisms differ but the hinge ingredients remain the same. These mechanisms are already well-known to structural engineers; all that has changed is that all of the support hinges are now doglegs. The doglegs permit 'exact' solutions by providing a load-path for shear onto supports. Notice that there is no yield of the transverse shear-reinforcement in any of these 'exact' mechanisms.

This author believes that strength and strain capacities at dogleg hinges may be systematically superior to those at mid-span hinges because of the extra constraints at the re-entrant support corner. This can only lead to increased strength and/or ductility as compared to mid-span hinges.

SHEAR-FAILURES FOR ORDINARY BEAMS

Fig 12 illustrates a skew-symmetric mechanism in which some strength but more ductility is lost to combined shear-bending failure. Notice that Fig 12 does involve extensive yield of both the longitudinal and the transverse shear-reinforcement. All of these yield-lines are rotational bending yield-lines and each rotates about a centre which is, in every case, located along the length of the same yield-line. There are no diagonal struts across any of these yield-lines although there is strut action elsewhere. This suggests that the 'strut-and-tie' and 'variable-angle strut' methods have a misplaced emphasis on struts rather than ties.

When one considers non-symmetric cases with gravity loads there are again a small number of mechanisms using hinge ingredients similar to those of Fig 12.

We do need to understand all of these shear-bending mechanisms so as to be able to design shear reinforcement sufficient to ensure that they are all, indeed, prevented, that is to force the more ductile bending failures with dogleg hinges. This can, and should, include allowance for over-strength and strain-hardening of the longitudinal reinforcement while the transverse reinforcement is limited to nominal or reliable yield-strength.

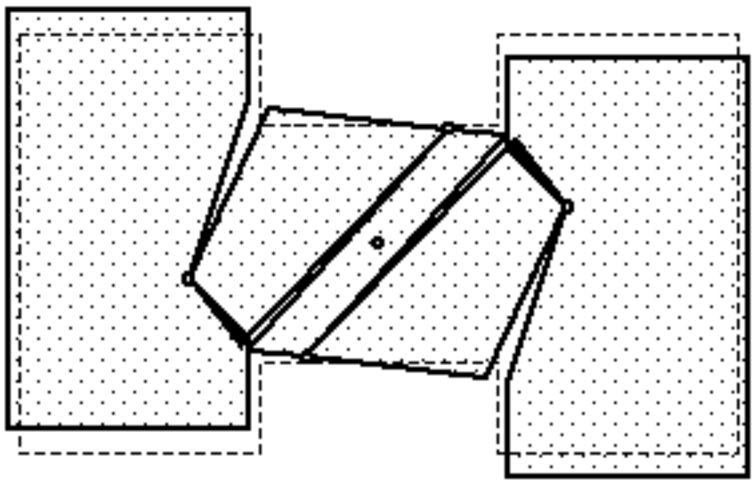

Fig 12: Steep mixed mechanism: displaced shape

CONCLUSIONS

This author has progressed the theoretical study of 'exact' yield-line collapse mechanisms to the stage where there are now explicit needs for laboratory research:

- To demonstrate systematic improved performance for support bending ('dogleg') hinges as compared to the mid-span (Whitney) 'plane-section' hinges codified in AS3600:2001.
- To provide a more complete understanding of the elasto-plastic effects of shear on the bending-strength of support hinges and
- To ensure that the strut-and-tie method in the draft AS3600 is, indeed, 'safe'.

The author understands that AS3600: 2009 will allow use of the 'strut-and-tie' method. For any given problem, there will be an infinity of 'strut-and-tie', 'variable-angle strut' and other arbitrary solely lower-bound equilibrium work-around solutions. For the same given problem, there will be a unique 'exact' yield-line solution. The 'exact' solution can always be repackaged as the optimum 'strut-and-tie' or 'variable-angle strut theory' solution although its primary focus will be on the ties rather than the struts.

As a retired structural designer, he has no significant laboratory experience so his contribution would largely involve theoretical aspects similar to those herein. He thinks that this work will have an effect, say on AS3600:2012 or later and he looks forward to that.

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