Round Determinate Panel Testing in Australia

Designers and contractors frequently encounter difficulties when using beams for the assessment of postcrack performance in fiber-reinforced shotcrete (FRS). The most common beam test used in North America is the ASTM C-1018 procedure (ASTM 1997), although alternatives exist, including the Japanese SF-4 procedure (JSCE 1984) and a multitude of European national standards.

by E. Stefan Bernard

In Australia, the most commonly used procedure is the EFNARC beam test (EFNARC 1996). This test is very similar in execution to the C-1018 test but involves a more slender beam measuring 75x125x550 mm (3x5x22 in) tested on a 450 mm (18 in) span. Despite their differences, all these procedures involve third-point loading of a saw-cut FRS specimen, with performance based on characteristics of the postcrack load-deflection record.

The problem for designers and contractors is that postcrack performance parameters based on beam tests often exhibit poor reliability. In a large-scale research program conducted by the author (Bernard 1999), and quality assurance (QA) testing involving beams tested in sets of three, the coefficient of variation in postcrack performance has averaged about 15% for the ASTM I_{50} index. The variation in within-batch performance commonly exceeds 20% for residual strength measured at 3.0 mm (1/8 in) central deflection in the EFNARC beam test. The result is that the mean performance of many batches of apparently adequate FRS fails to pass minimum requirements. In Australia, this has given rise to frequent disputes between concrete suppliers and shotcreting contractors over who is to blame for substandard performance.

Several years of routine QA beam testing led the author to suspect that the cause of many failures lay with the procedure itself. The area of concrete that experiences failure in a beam is very small compared to the volume of concrete contained within an FRS structure. Since performance is strongly dependent on the number of fibers that happen to occur at the crack, it is therefore quite likely that the performance of the beam is not representative of the majority of concrete in a structure.

Panel-based procedures such as the EFNARC panel test (EFNARC 1996) exhibit far better reliability than beams, but this procedure is not without its problems. Principal among these is the fact that the pattern of failure suffered by the specimen in this test depends on how flat the base of the panel is made. A truly flat specimen rests evenly on the flat support fixture during testing and results in a single peak in the load-deflection curve; a distorted specimen suffers uneven stressing and multiple peaks in the load-deflection curve as it progressively cracks and redistributes load. While some have argued that this mimics the redistribution of load that occurs during statically redundant failures of tunnel linings, this feature of the EFNARC test is not attractive from the viewpoint of QA testing, which seeks to assess materials in a consistent manner.

In an attempt to improve upon the EFNARC test, the author developed the round determinate panel test (Bernard 1998). In this procedure, a round FRS specimen measuring 75x∅800 mm (3x31 in) is supported on three symmetrically arranged pivots

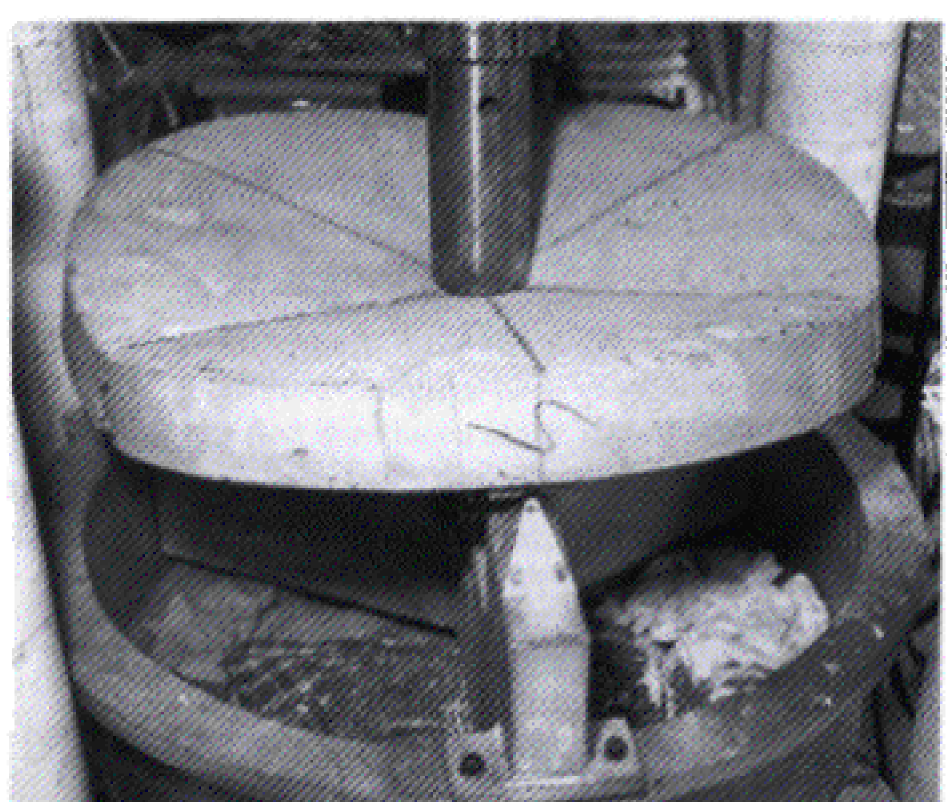

Figure 1. Failure of a round determinate panel in three segments.

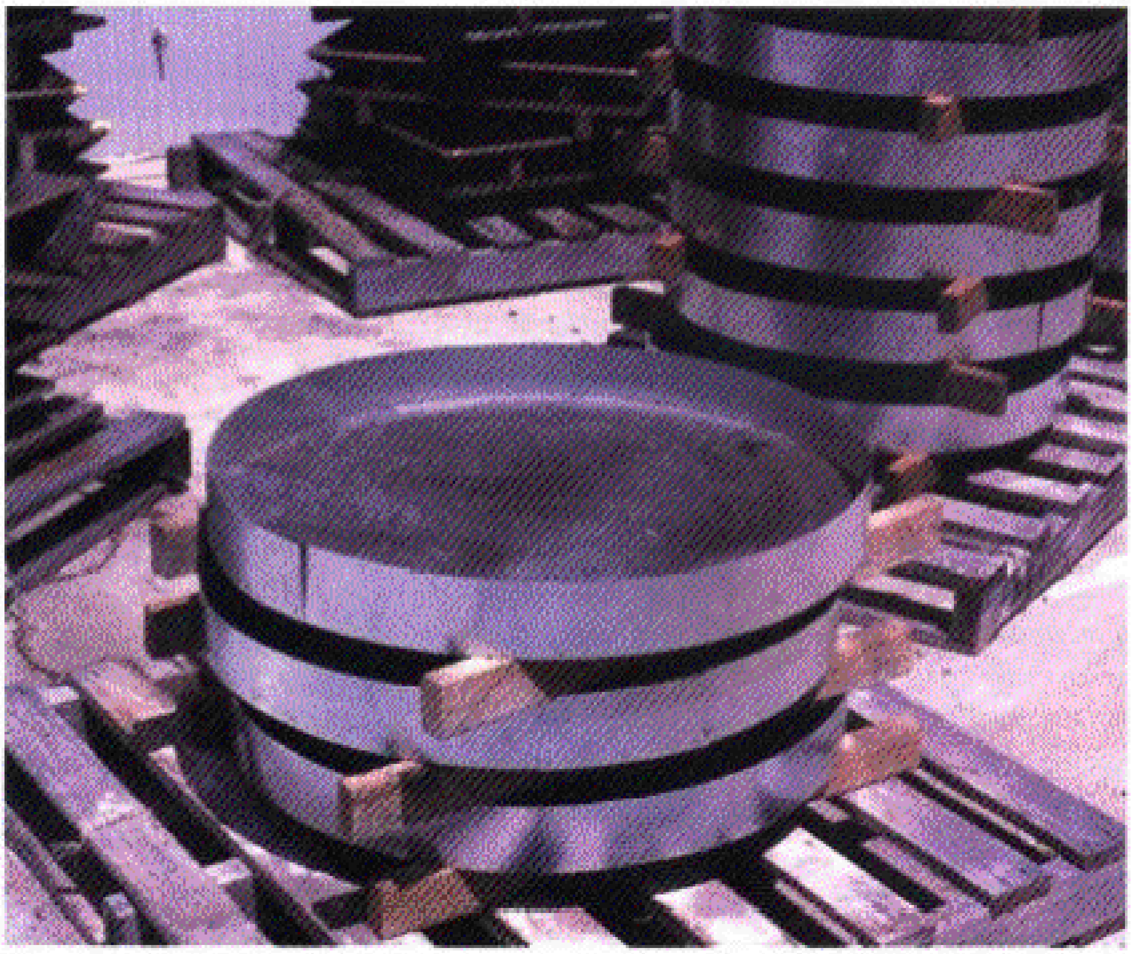

Figure 2. Plywood forms ready for panel spraying.

displacement and measuring resistance as a function of deformation. This requires a servo-hydraulic or screw-driven loading mechanism that can operate without the intervention of an operator. A load-controlled test machine is not adequate. Performance is measured as the load to cause first crack of the concrete matrix, and cumulative energy absorption up to selected values of central deflection. In Australia, these values have been 5 and 40 mm ($^3/_{16}$ and $1^1/_2$ in) central deflection. Following a test, the thickness of the specimen is measured at a number of points along each radial crack, and a fiber count is carried out at 100 mm (4 in) intervals along the cracks. A very reliable estimate of the mean fiber density in the FRS can be obtained by counting the fibers protruding from 10x100 mm ($^3/_8$ x 4 in) long portions of crack.

placed on a 750 mm (30 in) diameter pitch circle diameter. Under a central-point load, the specimen almost always fails through the formation of three radial cracks that run from the center and bisect each unsupported sector of the panel (Figure 1). This pattern of failure occurs regardless of tolerances on the flatness of the specimen base, and the total length of crack amounts to 1200 mm (47 in). The result is a coefficient of variation in postcrack performance parameters (based on energy absorption) of about 6%. The reliability of this test exceeds that of any other published procedure for the assessment of postcrack performance.

PRODUCTION AND TESTING

Formwork for round determinate panels (RDP) typically consists of a round plywood base to which a sheet steel strip is nailed, producing a dish (Figure 2). The width of the steel strip is chosen to produce a final depth of 75 mm (3 in) inside the dish. Timber runners can be fastened to the base of the form to facilitate easier handling of the hardened specimen, which generally weighs about 90 kg (198 lbs). The form can be secured to a frame for vertical or overhead spraying if desired, or can be inclined against any convenient object during production (Figure 3). Once the form is full, the surface must be screeded to produce a flat specimen of uniform thickness. Maintenance of uniform thickness is an important step toward achieving low variability, because performance is strongly dependent on the final thickness and uniformity of the specimen.

Round determinate panels are tested by imposing a central point load at a controlled rate of

The heavy mass of a hardened panel specimen does not present a problem on most construction sites because handling equipment is generally available to move such bulky objects. Indeed, round determinate panels are smaller than the square panels from which beams are commonly cut. However, unlike beams, round determinate panels do not require cutting; they are simply stripped from the form and cured by whichever means is deemed adequate.

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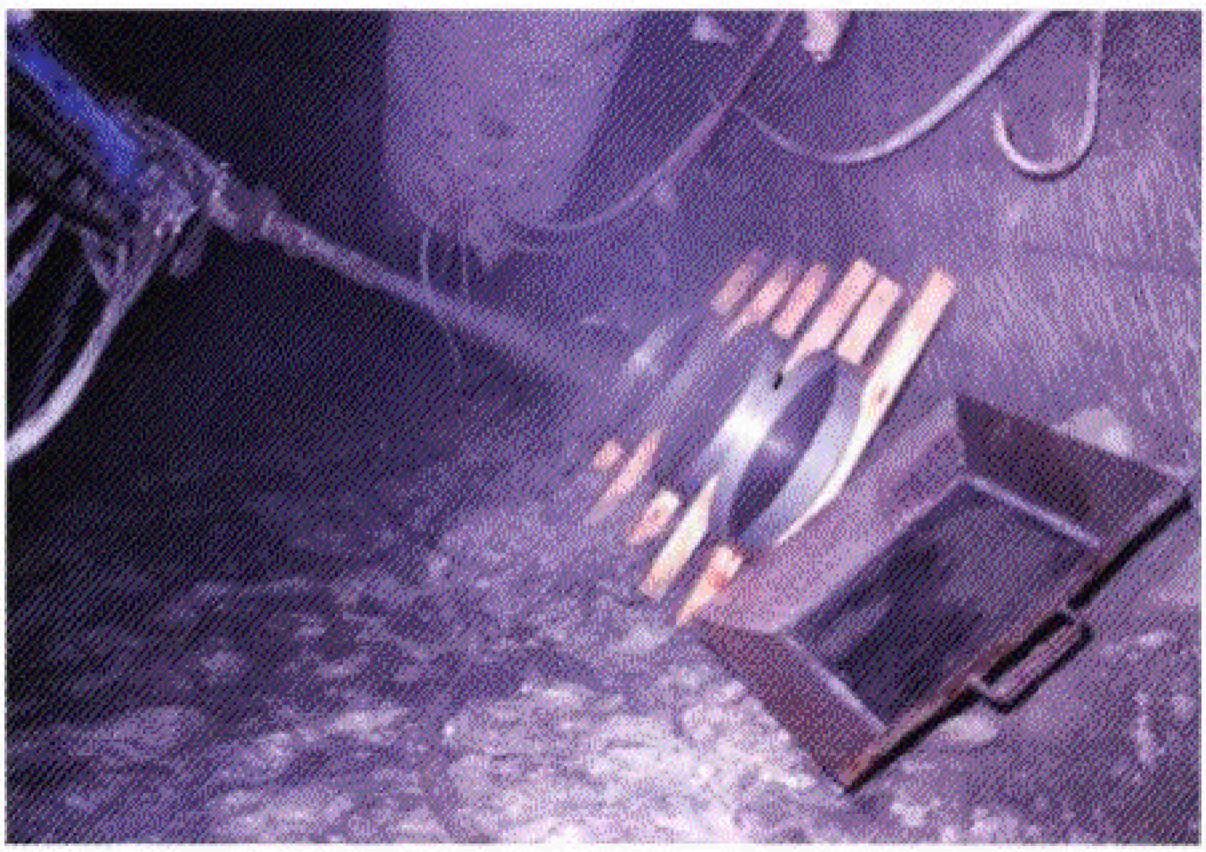

Figure 3. Specimen production in an underground environment.

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Round determinate panels, therefore, present an important logistical advantage over beams and EFNARC panels in that saw cutting is entirely eliminated from the QA process. This is a welcome factor from the contractor's point-of-view since concrete cutting is a costly, dirty, time-consuming, and very noisy activity. In a large tunnelling project currently under way in Sydney, saw cutting has accounted for 30% of the total cost of QA testing for postcrack performance assessment. Considering the superior reliability of round determinate panels, and the consequent reduction in the number of specimens required per sample, the overall cost of QA testing is significantly lower when based on round determinate panels compared to beams.

PERFORMANCE DATA

The cry has often been heard that shotcrete contractors and researchers do not need another test procedure for FRS because so many already exist. The proliferation of tests that has occurred in recent years has resulted in widespread confusion regarding the most appropriate to use and about correlations in performance between the alternatives. In response to this, the author has undertaken a large-scale study examining correlations in the performance of beams and panels for numerous steel and synthetic fiber-reinforced shotcrete mixes. The results are presently available as a report (Bernard 1999), but will soon be published more widely. Data from this study shows a strong correlation in energy absorption between the EFNARC square panel test and the RDP procedure, and a clear relation between residual strength at 3.0 mm (1/8 in) central deflection in the EFNARC beam test and energy absorption at large deflections in the RDP test.

These correlations are important because many existing FRS linings were designed and constructed on the basis of performance data obtained from EFNARC beams and panels, particularly in Europe. Data from these projects can therefore continue to be used to develop suitable performance requirements for future designs, but with QA based on the round determinate panel test. The superior reliability and lower cost of this procedure can therefore be exploited immediately.

SUMMARY

A new, more reliable test for FRS performance that also offers cost advantages and a simplification of onsite operations has been developed in Australia through large-scale research and QA programs. The test is based on round determinate panels produced by spraying FRS into simple plywood molds. The procedure has proven satisfactory both in the laboratory, where more than one thousand specimens have already been produced and tested, as well as in construction practice, where several hundred have been tested as part of a QA program for a major tunnelling project.

Editor's note: The round determinate panel test is currently under review for standardization by the ASTM C09.42 Fiber Concrete Committee. A draft standard is currently being balloted.

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