SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

Final Project Report

Title: TESTING OF TUNNEL SUPPORT: DYNAMIC LOAD TESTING OF ROCK SUPPORT CONTAINMENT SYSTEMS (EG WIRE MESH)

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Executive Summary

In 1993 a series of tests on conventional and yielding rockbolts was completed using impulsive loading to evaluate the performance of these **retainment** support elements under simulated rockburst loading. For a support **system** to be fully effective in rockburst situations, and to maximise the safety under such conditions, the support system must also be able to **contain** rock material which is usually ejected with force in rockburst events. Such testing of **containment** support systems under dynamic loading is described in this report.

The essential objective of the project was to determine the performance characteristics of containment elements of tunnel support in common use in South African mines under dynamic loading. The magnitude of the energy levels in this testing had to be compatible with that which could be expected to be encountered during reasonably severe to significantly large rockbursts. To achieve this a drop weight test facility was designed and constructed with the following capabilities, considered to be representative of severe rockbursts:

- input energies up to approximately 70 kJ;
- impact loading velocities up to approximately 8 m/s.

Testing was carried out on "panels"of containment support 1,6m x 1,6m. A simulated rock mass consisting of concrete blocks was in contact with the support and a load distribution pyramid of steel-encased concrete blocks was formed above this. The test panel was suspended from four rockbolts at 1m centres.

In total, 56 tests were carried out representing combinations of different types of wire mesh, wire rope lacing, and fibre reinforced shotcrete. From the results of the test programme, the following general conclusions and deductions can be made with a considerable degree of confidence:

- the lacing is the most important single element in the containment component of a

tunnel support system subjected to significant dynamic loading;

- lacing can, however, be too strong (and hard) for other presently-used elements e.g. de-stranded hoist rope strands of greater than 14 mm diameter could cause failure of the tendon connections;
- some yieldability of the lacing is necessary, and over-tensioning (in excess of 10 kN) is probably detrimental in that it may increase the likelihood of failure of the smaller diameter ropes or of connecting elements;
- the performance limits of all elements of a mesh/lacing containment system should be **balanced**, that is, compatible with the capabilities of the retaining elements;
- bearing plates formed by conventional punching or guillotining of 6 mm mild steel plates are not compatible with mesh. Diamond mesh in particular is vulnerable in this respect. The standard face-plates could, and should, be easily improved;
- most elements of the containment system can be significantly improved;
- a containment system utilizing presently available mesh and lacing with improved connectors and available yielding tendons **spaced at 1 m centres**, can be expected to withstand a "once-off" rockburst of 50 kJ/m^2 intensity. This would be considered a **severe** event.

Recognizing strictly that it is within the context of 1,0 m spacing between rockbolts, the following specific conclusions can be drawn:

- without lacing, diamond mesh is superior to weld mesh as the containment element under low energy dynamic conditions up to 15 kJ/m^2;
- with appropriate lacing, weld mesh is better than diamond mesh at higher energy levels as it is less prone to unravelling, allowing the spill-out of rock fragments;
- the yieldability of weld-mesh can be improved without major difficulty. Together with the more easily installed and efficient zig-zag lacing pattern and chain-link connectors, such improved weldmesh could, it is believed, contain the damage from a 70 kJ/m^2 event which would probably represent a major rockburst.

Shotcrete with dispersed reinforcement, as provided by suitable steel or polymer fibres, appears to be well suited as cladding or containment in tunnels subject to seismic risk.

Preliminary indications are that fibre-reinforced shotcrete could be used together with suitable yielding tendon support at 1 unit/m^2 density in areas where low-intensity rockbursts might occur. Where impulses of about 10 kJ/m^2 occur, a fibre-reinforced shotcrete layer would probably provide adequate cladding. However, it is necessary to recognize that corrosion could seriously impair the longer term strength of cracked shotcrete if steel fibres are used as the dispersed reinforcement. In the case of polypropylene fibres, the ability of the shotcrete cladding to contain succeeding rockbursts appears to be limited.

Indicative design recommendations, based on the assumption of a 1m rockbolt spacing, are provided in the report.

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SAFETY IN MINES RESEARCH ADVISORY COMMITTEE
PROJECT NO. GAP 221

TESTING OF TUNNEL SUPPORT: DYNAMIC LOAD TESTING OF ROCK SUPPORT CONTAINMENT SYSTEMS (eg WIRE MESH)
FINAL REPORT - AUGUST 1997

1 INTRODUCTION

In 1993 a series of tests on rebar rockbolts and cone bolts was completed using impulsive loading to evaluate the performance of these **retainment** support elements under simulated rockburst loading. In these tests the impulsive loading was applied with the use of explosives. The test results demonstrated graphically the ineffectiveness of conventional rebar support elements in withstanding rockburst loading, and the success that the yielding cone bolts showed in containing the "rockbursts" with no damage to the elements. The tests were specifically on the **retaining** portion of the support systems. For a support system to be fully effective in rockburst situations, and to maximise the safety under such conditions, the support system must also be able to **contain** rock material which is usually ejected with force in rockburst events. It was therefore necessary to test **containment** support systems under dynamic loading to the level experienced during rockbursts. Such testing was proposed as the project GAP 221.

Project GAP 221 was commenced in 1995, with the following expected primary output:

- capabilities of alternative containment systems under simulated rockburst conditions would be determined;
- information for rockburst support design specifications would be provided;
- design data for specific containment support elements and systems would be provided.

The potential impact of the research work was expected to be:

- dissemination of information to the mining industry on the performance of rock containment systems used by the industry;
- provision of valuable information for the development of improved support systems;
- improvement in safety in mines through better design;
- improvement in support capability.

The SIMRAC Research Proposal is included in Appendix A for record purposes.

2 METHODOLOGY

The essential objective of GAP 221 was ***to determine the performance characteristics of containment elements of tunnel support under dynamic loading in a realistic operating environment at energy levels that could be expected to be encountered during reasonably severe to significantly large rockbursts.***

In a real rockburst situation, the loading imposed on containment support is in the form of a violent impact of the rock mass distributed across the surface of the containment support. In this form of loading the retainment elements (rockbolts and face plates), the containment support, and the rock mass itself all play a part. It was therefore considered to be important to take all of these aspects into account in the test programme. The method of testing adopted therefore involved the following:

- dynamic loading of a representative area of containment "fabric" by the dropping of a mass;
- containment support retained by rockbolts and face plates;
- distribution of load onto the containment support through a "rock mass";
- simulation of the fractured rock mass using layers of concrete blocks which would participate in the loading and deformation;
- a large area of containment support to take into account the areal continuity of the support.

It was recognised that a test facility incorporating all of the above concepts would be complicated, and that, although it would be easy to determine the total energy input, it would not be possible to define the portion of that energy actually imposed on the containment support itself. However, the aim was to achieve a series of repeatable loading conditions which would allow the comparative performance of different support systems to be determined. An indicator of the degree of realism of the tests would be the achievement of damage which has a similar visual appearance to that often observed after rockbursts underground. Photo 1 in Appendix C shows damage to a mesh and laced portion of an extensive network of tunnels that suffered severe damage after an event of magnitude $M_L = 3.6$.

It was essential that the test system could provide energy inputs that would correspond with significant rockburst events. An energy-absorption capability of 25 kJ/m^2 has been suggested in the technical literature as the necessary requirement for tunnels subjected to "reasonably severe rockbursts". The maximum energy capacity of the drop weight system in the test facility was 70.6 kJ which is believed to be in excess of the energy imposed on support during a significantly large rockburst.

2.1 Test Geometry Definition

To define the size of containment support "sample" that would be required and the support and loading arrangement for the tests, the following concepts were decided on:

- for a containment system of wire mesh only, or wire mesh and lacing, a 2m x 2m area of mesh would be supported by four rockbolts spaced 1m apart. The central rockbolt- supported area would be subjected to the dynamic loading;
- for shotcrete reinforced with wire mesh or with steel or polypropylene fibres, the size of the panel prepared would allow for an overlap of 300 mm outside of the rockbolt area of 1,0 m x 1,0 m. The test panel would thus be 1,6 m x 1,6 m;
- the load distribution system would consist of packed concrete blocks in direct contact with the containment support to simulate the rock mass, and a pyramid of steel-clad, load-distribution elements above this to distribute the imposed load to the whole of the central containment support surface;
- The edges of the test panel would be constrained by suitably dispersed tractions to have only limited movement downwards and inwards. The test section could thus be regarded as representative of any portion of a tunnel suffering more-or-less uniform damage over an extended area. Photo 2 in Appendix C shows the arrangement of the various elements as assembled prior to a test on a sample of weldmesh.

2.2 Design of Test Facility

The design of the test facility is best illustrated by the drawings in Figures 1 and 2. This facility was designed to enable "samples" to be tested with impact loading at velocities up to approximately 8 m/s, and energy inputs up to approximately 70 kJ. The drawing in Figure 1 illustrates the following:

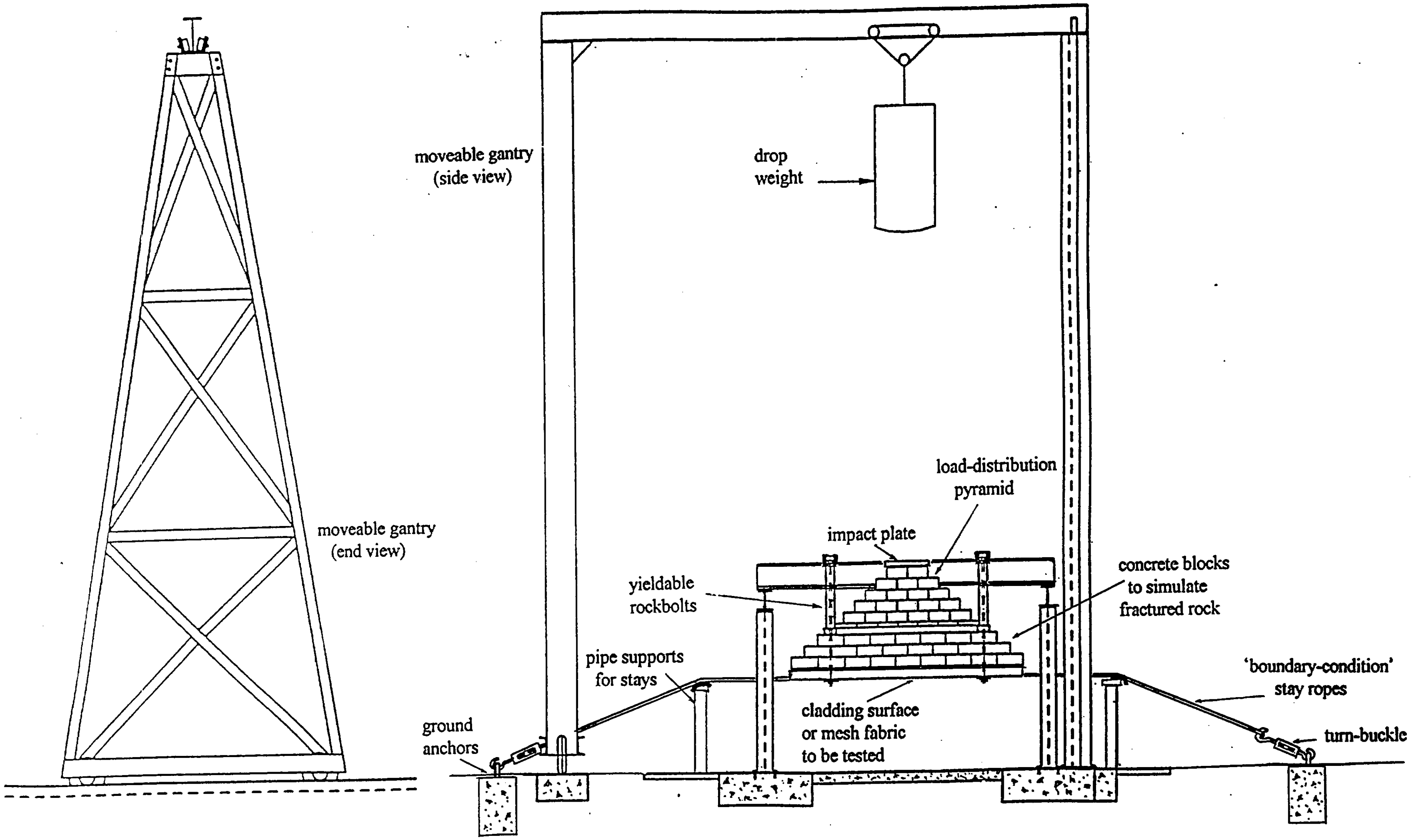
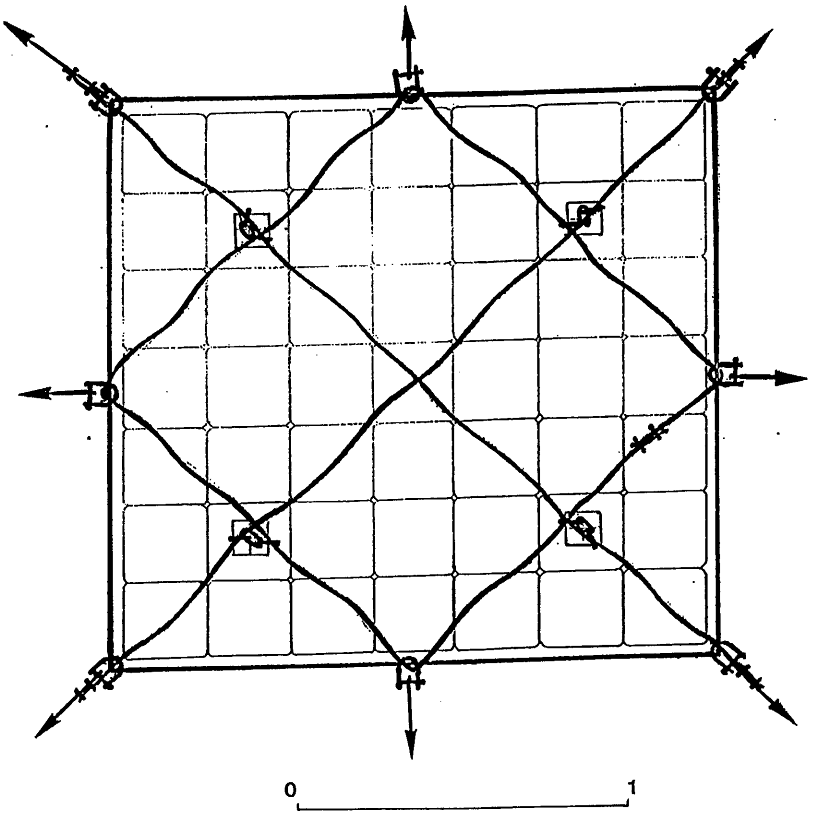


Figure 1: Diagrammatic Sketch of Test Facility

a) normal ‘cross-over’ pattern



b) ‘zig-zag’ pattern

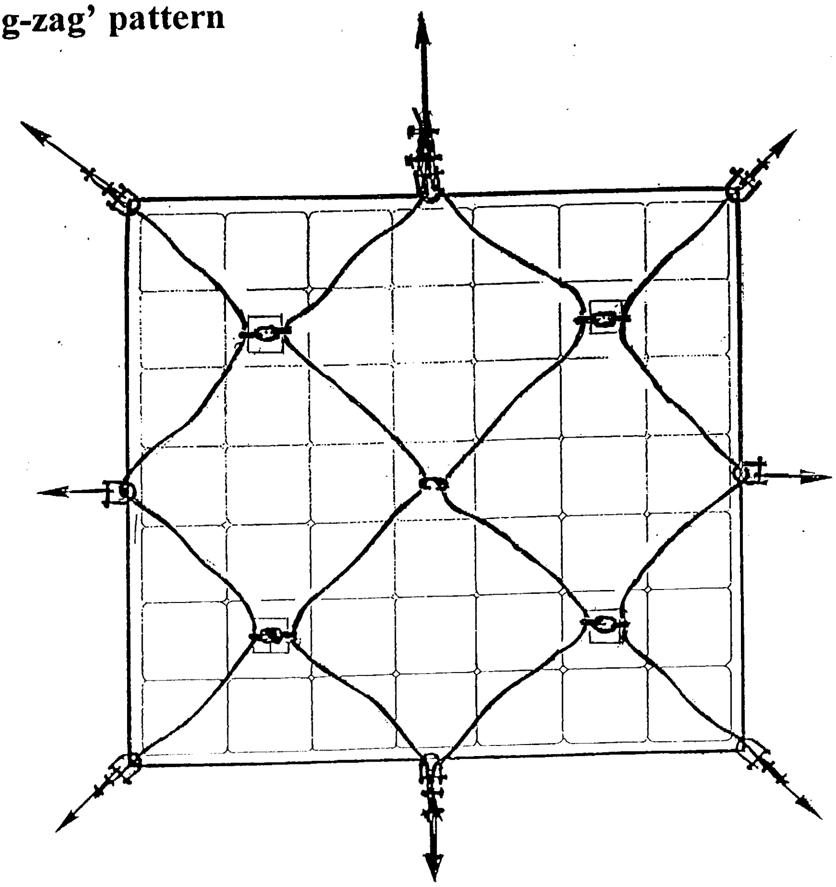


Figure 2: Arrangement of Lacing and Boundary Condition Frame

- the containment support "sample" is hung from support beams using four 22 mm diameter cone-bolts;
- the simulated rock mass and the pyramid of loading elements;
- the traversing load suspension frame, and the drop weight;

Also illustrated on Figure 1 are the "boundary-condition" stay ropes that provide the external transverse support of mesh and lacing to simulate the "infinite" extent of the support and to prevent the influence of edge effects as far as possible. The boundary-condition frame consisted of 25 mm diameter bars around which each strand of the mesh test piece would be wrapped and tied-off securely.

The corners and mid-points of the sides of the frame were coupled to the stay ropes by means of heavy shackles as shown in Figure 2.

The lacing under test was generally arranged in the pattern shown in Figure 2(a), where one length of lacing strand was hooked through the mid-point shackles with its ends overlapped and joined by means of two Crosby clamps to form a continuous "diamond". No slipping ever occurred at this join because relatively little strain was imposed on the "diamond".

The two main diagonal lacing strands passed through the corner shackles to be overlapped with, and directly clamped to, the corner stays by means of three Crosby clamps. Slippage sometimes occurred at these connections when the higher values of impulse energy were imparted to the test panel. A somewhat simpler "zig-zag" pattern, Figure 2(b), was also used in some tests.

Tension of between 5kN and 10kN, usually, was applied to the stay ropes by means of large turnbuckles which ensured that the lacing supporting the test mesh was reasonably taut. Two drop weights with masses of 1048 kg and 2706 kg were available to provide maximum energies of 38 kJ and 70,6 kJ at velocities of 8,5 m/s and 7,3 m/s respectively.

It is to be noted that, since the aim was to determine the performance of **containment** support systems, yielding cone bolts were used specifically to ensure that failure of bolts did not occur in the tests. Had rockbolts failed during the tests, the test results could have been confused, since both retainment support and containment support would have contributed to the behaviour.

Construction of the test facility commenced early in 1995 and the first preliminary test was performed on 19 December 1995. After minor modifications to the testing facility the test programme commenced on 9 February 1996. The test facility is illustrated in photographs 3 and 4 presented in Appendix C.

2.3 Testing Method and Preliminary Evaluation

The measurement of deformation of the containment support surface was made by a direct tape-rule reading of the change in elevation with respect to a reference surface just above the concrete floor. These measurements were carried out at 8 marked positions on the concrete bricks representing the supported rock surface, as shown in Figure 3.

Still photographs were taken before and after, and sometimes during, the impact of each test drop. A video record was also made of each test.

Damage to the mesh and sometimes to the lacing was assessed by counting broken wires and taking close-up photographs where appropriate. An additional crude indication of damage was provided by the number of concrete bricks broken.

A preliminary test was carried out using a containment support "sample" consisting of weldmesh without lacing. This sample was subjected to sequential impacts from the drop weight until failure of the support occurred, with drops taking place through heights of 30, 200 and 300 mm. These represent theoretical impact velocities of 0,77, 2,0 and 2,45 m/s respectively.

Deflections of the support were measured during the preliminary test at the 8 locations

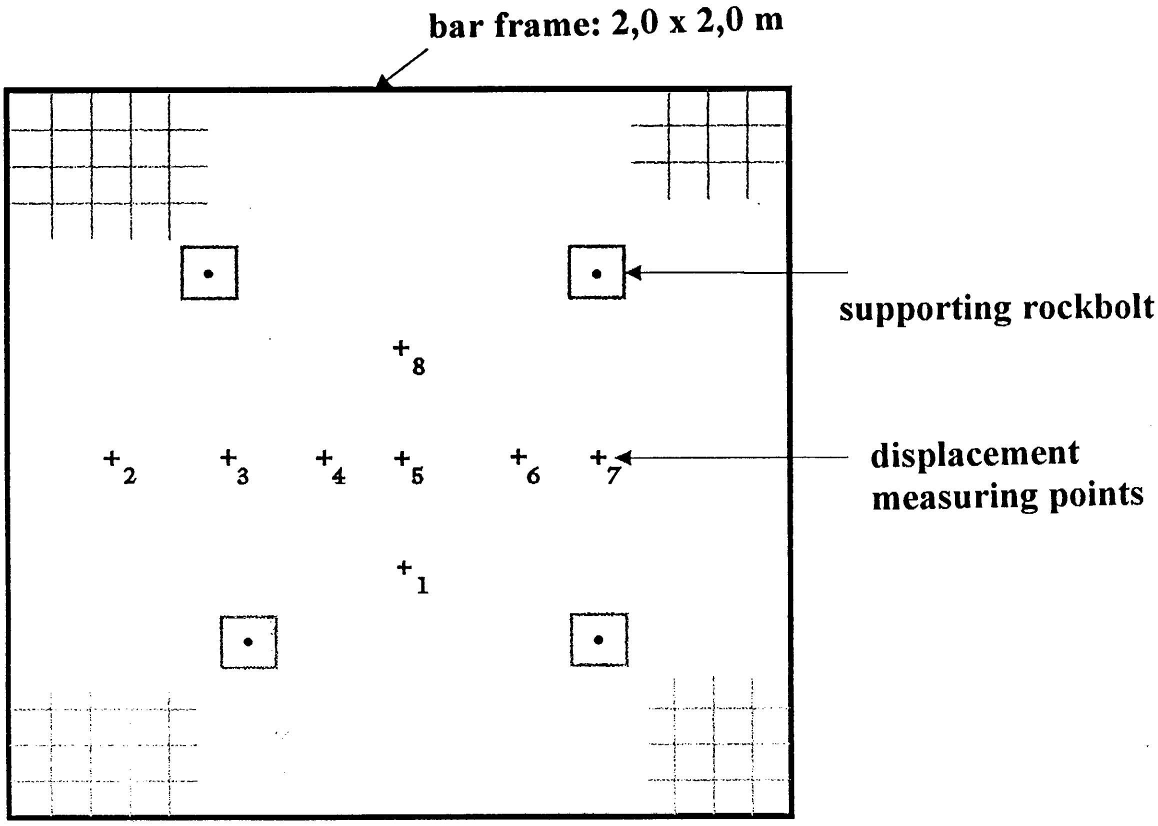


Figure 3: Layout of Displacement Measuring Joints

shown in Figure 3, and the deflection curves are presented in Figure 4. Although these 8 measurements of deflection were made routinely before and after each drop, the displacements generally turned out to be sufficiently symmetrical to permit total deformation to be characterized by specifying only the single value of deflection at the centre of each test specimen.

3 PRESENTATION OF DATA

The approved project proposal allowed for some 45 tests which would include the preliminary testing of four or five shotcrete panels. In fact 56 tests were carried out, which included nine tests on shotcrete panels. The results of all tests will be presented in this final report.

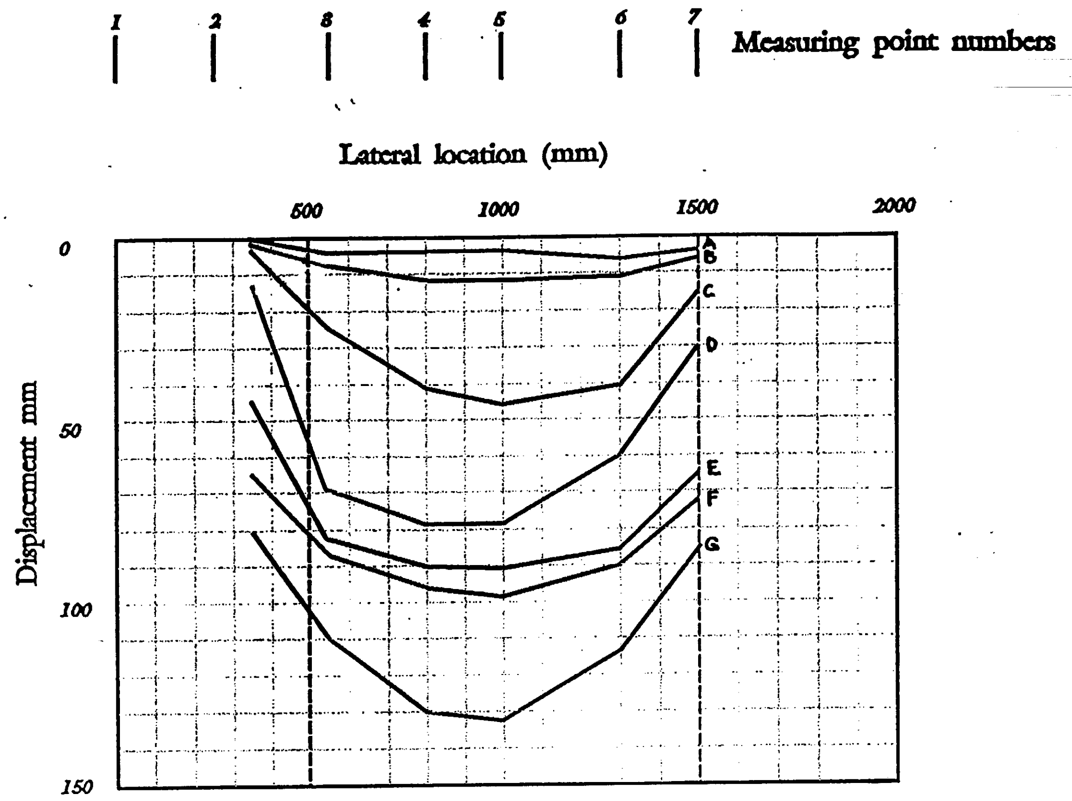
The 56 tests which constitute the GAP 221 project have been grouped into 14 series. These are shown in Table 1.

The detailed specifications of the test parameters and summaries of the damage description are tabulated in tables B1 to B14 in Appendix B.

The relationship between total energy input and deflection of the containment support after the test, for all of the series involving wire mesh, are shown in a composite plot in Figure 5. Individual results for each series are shown in Figure 6 to 14. The energy versus deflection relationships for the shotcrete tests are presented in Figure 15.

The most apparent and easily quantifiable damage to the mesh 'fabric' is the number of individual wires that are broken. The most important assessment is how these affect the stability of the mesh as a whole. This damage is described in the tables in Appendix B by listing the number and location of broken strands.

Also enumerated in the tables is the number of concrete blocks found to be broken after the test. Figure 16 shows that this number is strongly correlated with the energy of impulse. While such a trend is to be expected, the closeness of correlation is indicative



KEY

ZERO : Set up with concrete blocks and load distribution pyramid

A : Drop weight imposing static load

B : Drop weight impact through 30 mm

C : Drop weight impact through 200mm

D : Drop weight impact through 300 mm

E : Drop weight impact through 200mm

F : Drop weight impact through 200 mm

G : Drop weight impact through 300mm

Figure 4: Mesh Displacement after Repeated Impacts

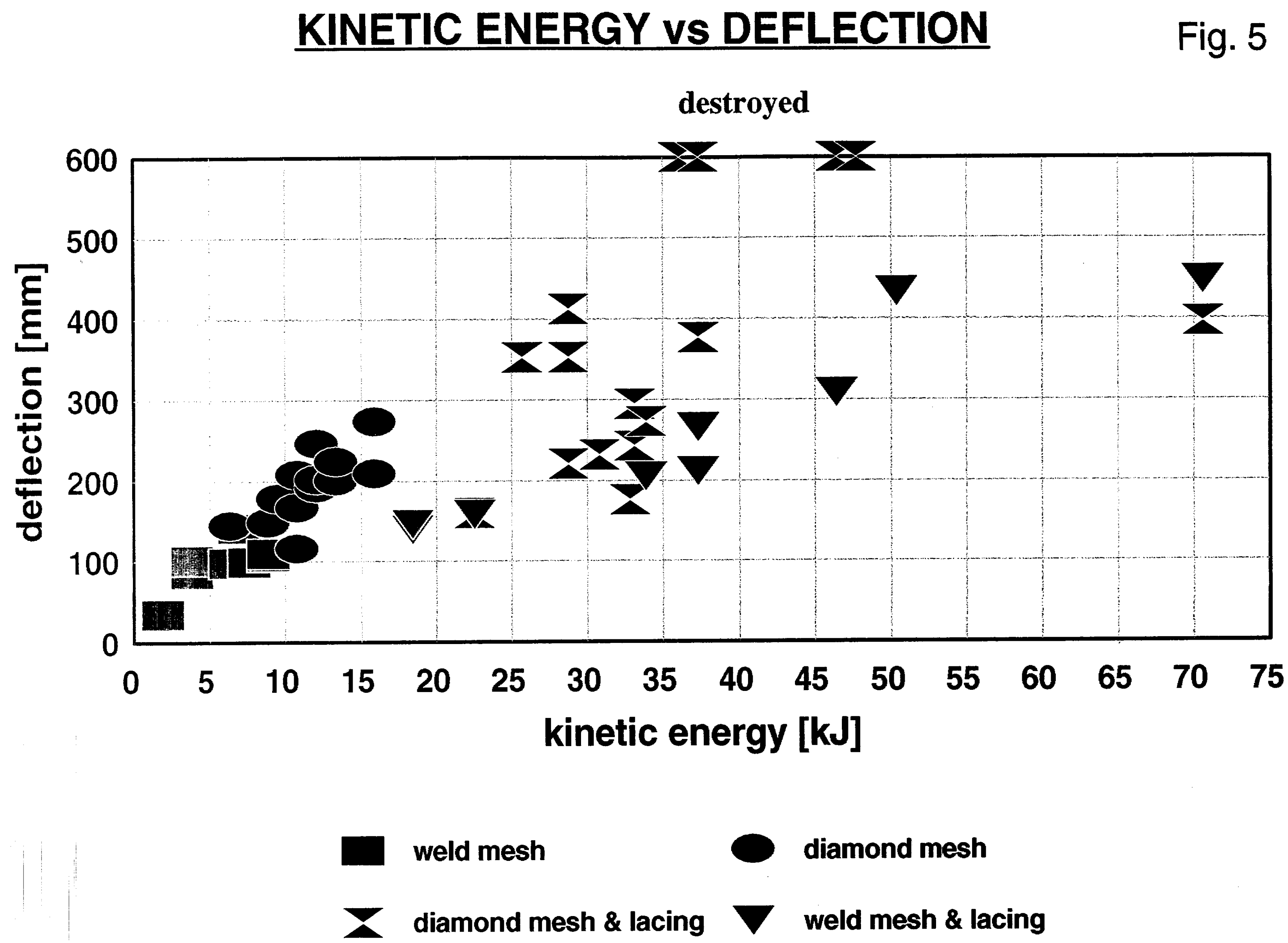

KINETIC ENERGY vs DEFLECTION
destroyed
deflection [mm]
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
kinetic energy [kJ]
■ weld mesh
● diamond mesh
⧗ diamond mesh & lacing
▼ weld mesh & lacing

Fig. 5

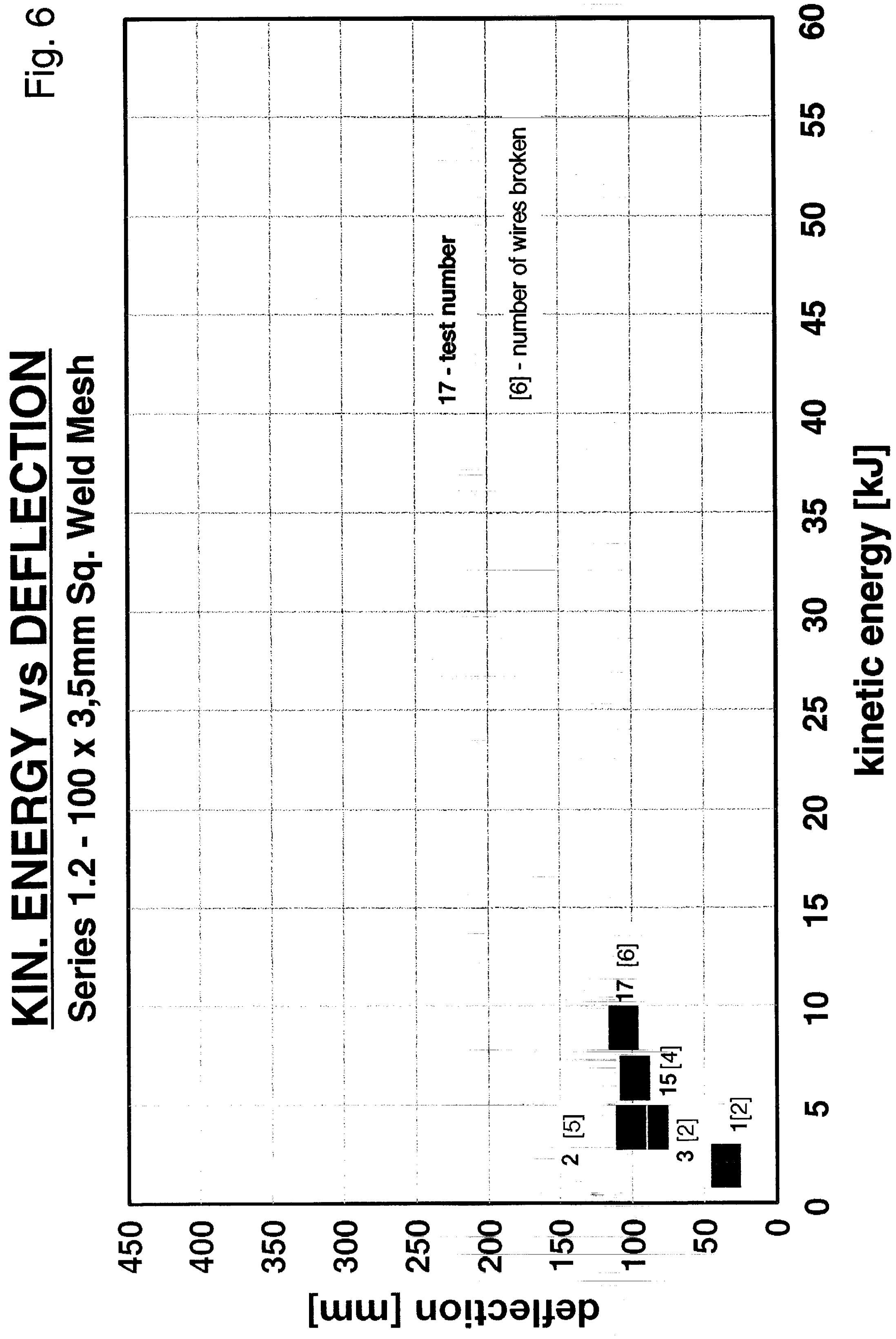

KIN. ENERGY vs DEFLECTION
Series 1.2 - 100 x 3,5mm Sq. Weld Mesh
deflection [mm]
450
400
350
300
250
200
150
100
50
0
kinetic energy [kJ]
0
5
10
15
20
25
30
35
40
45
50
55
60
17 - test number
[6] - number of wires broken
2 [5]
3 [2]
1 [2]
15 [4]
17 [6]

Fig. 6

KIN. ENERGY vs DEFLECTION

Series 1.3 - 100 x 4mm Sq. Weld Mesh

Fig. 7

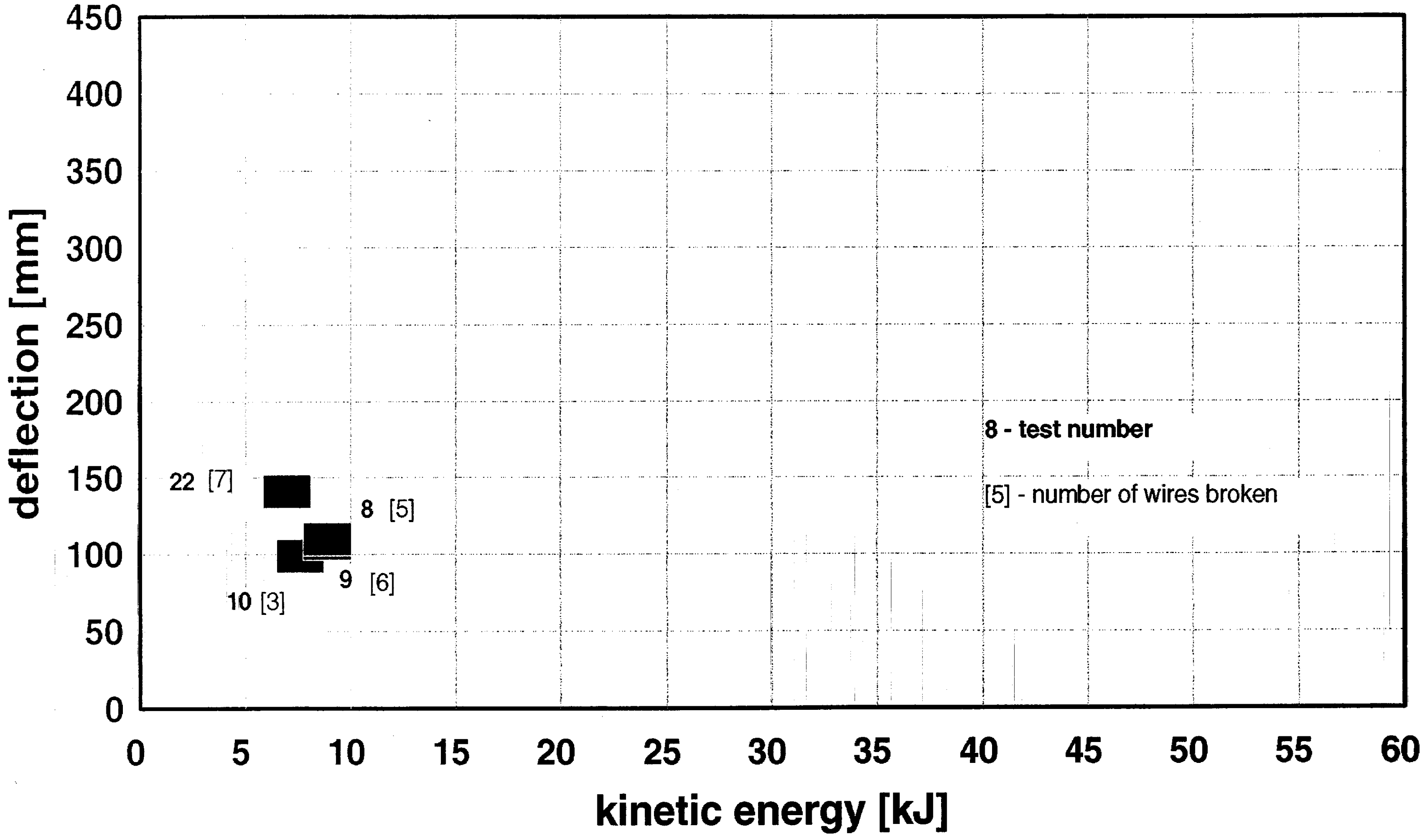
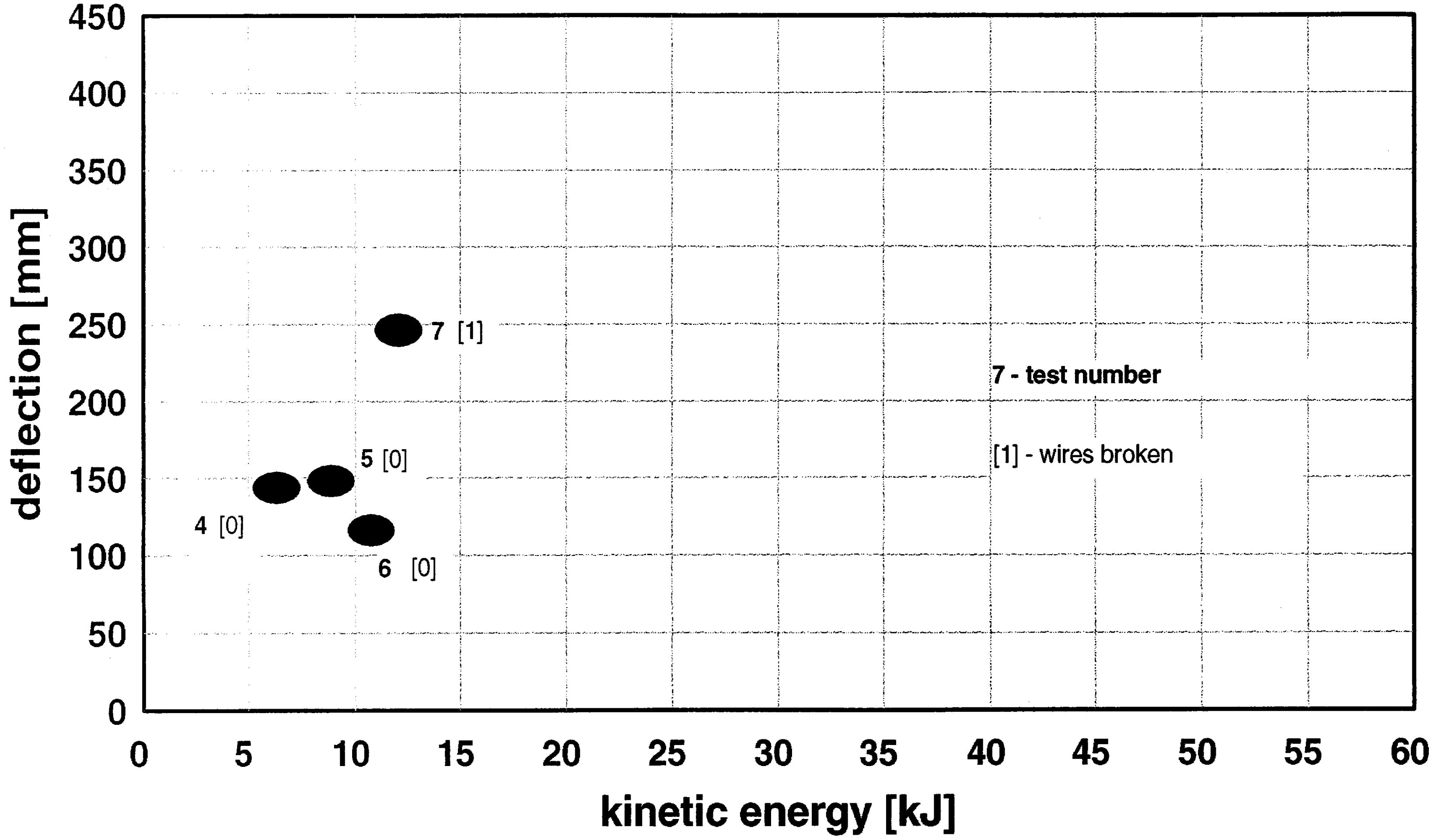


Fig. 8

KIN. ENERGY vs DEFLECTION

Series 2.1 - 100 x 3,2mm Diamond Mesh



KIN. ENERGY vs DEFLECTION

Series 2.2 - 75 x 3,2mm Diamond Mesh

Fig. 9

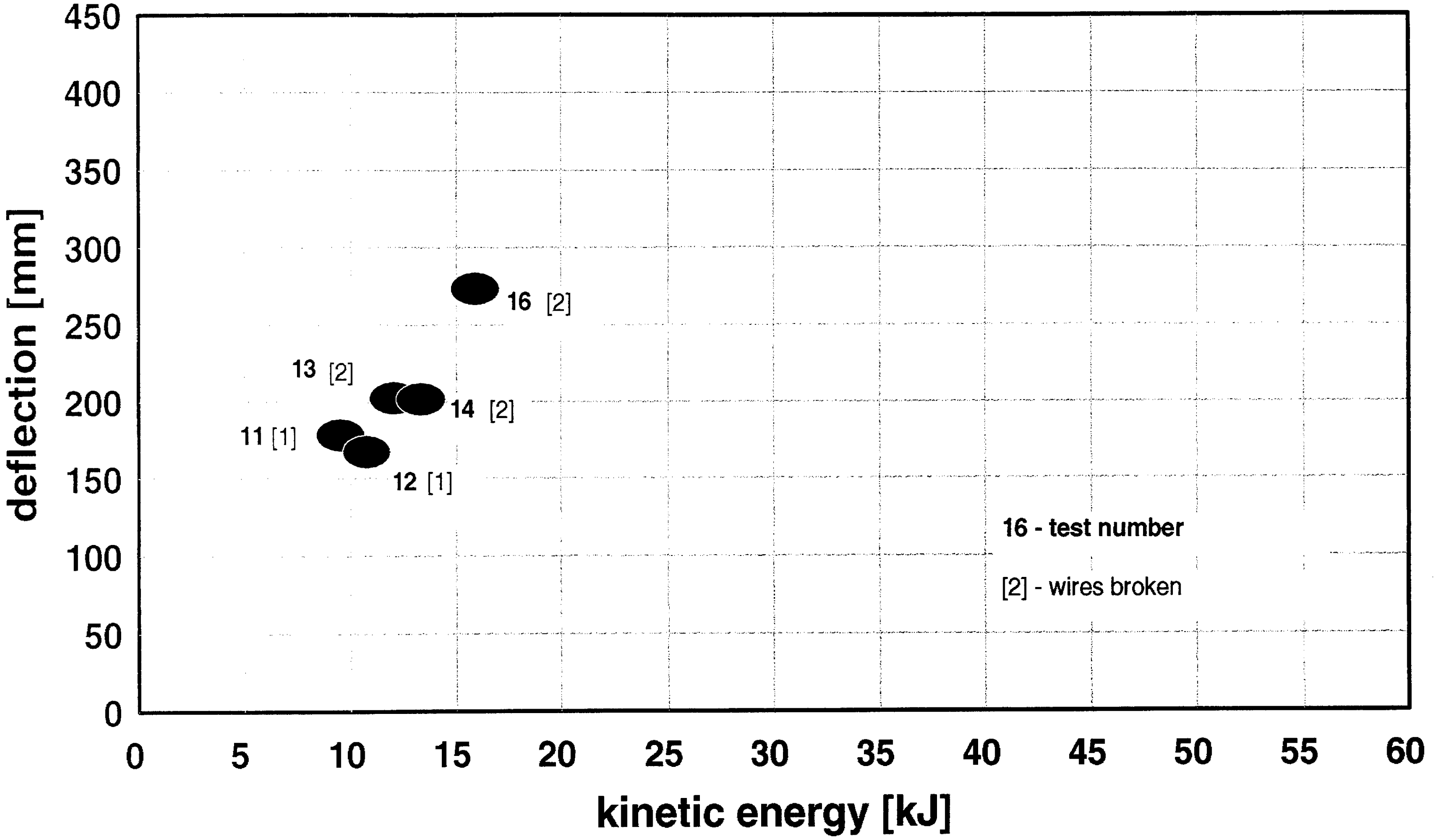
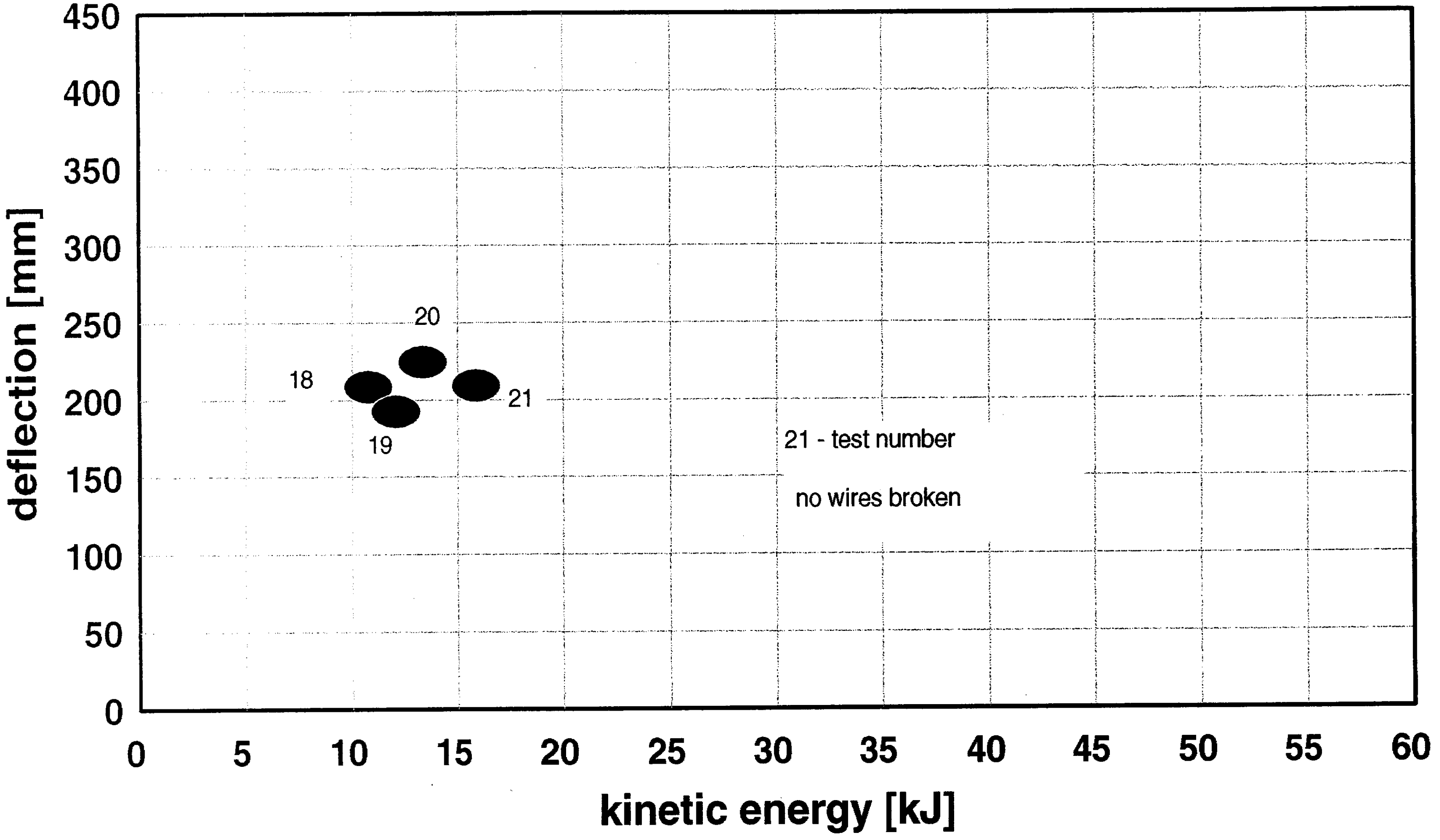


Fig. 10

KIN. ENERGY vs DEFLECTION

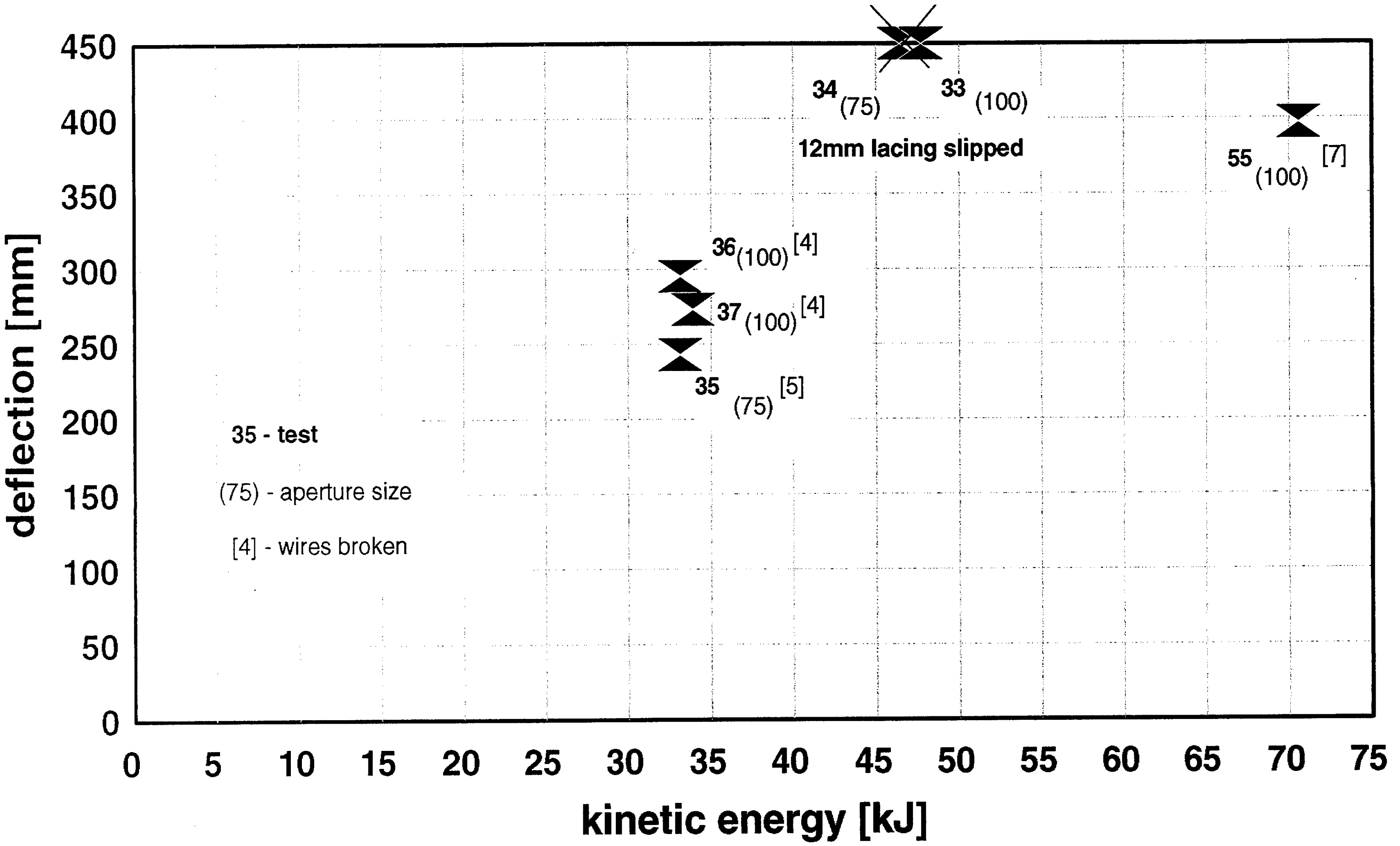
Series 2.3 - 100 x 4mm Diamond Mesh



KIN. ENERGY vs DEFLECTION

Fig. 11

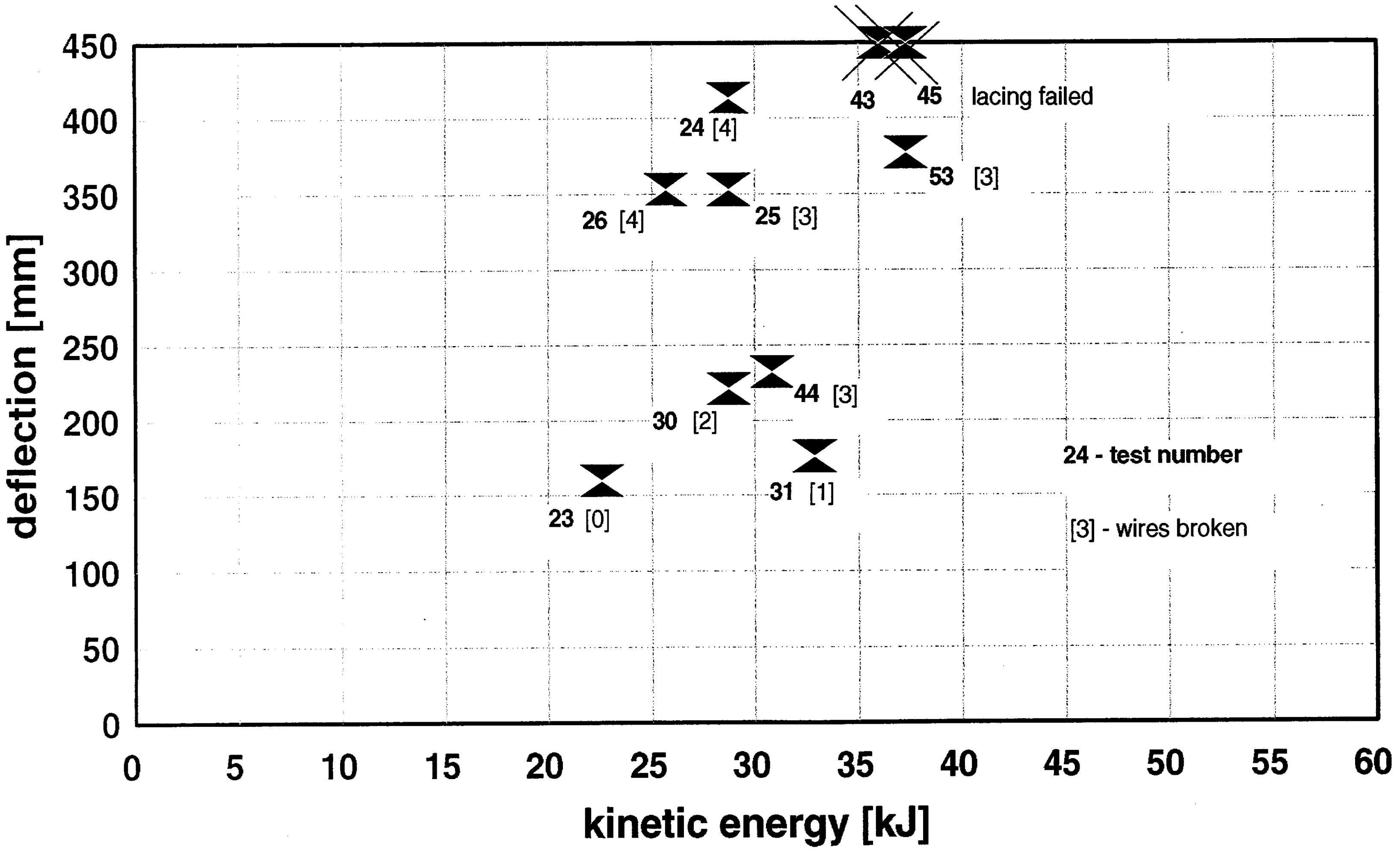
Series 3.1 & 3.2 - 75 & 100 x 3,2mm Diamond Mesh & Lacing



KIN. ENERGY vs DEFLECTION

Fig. 12

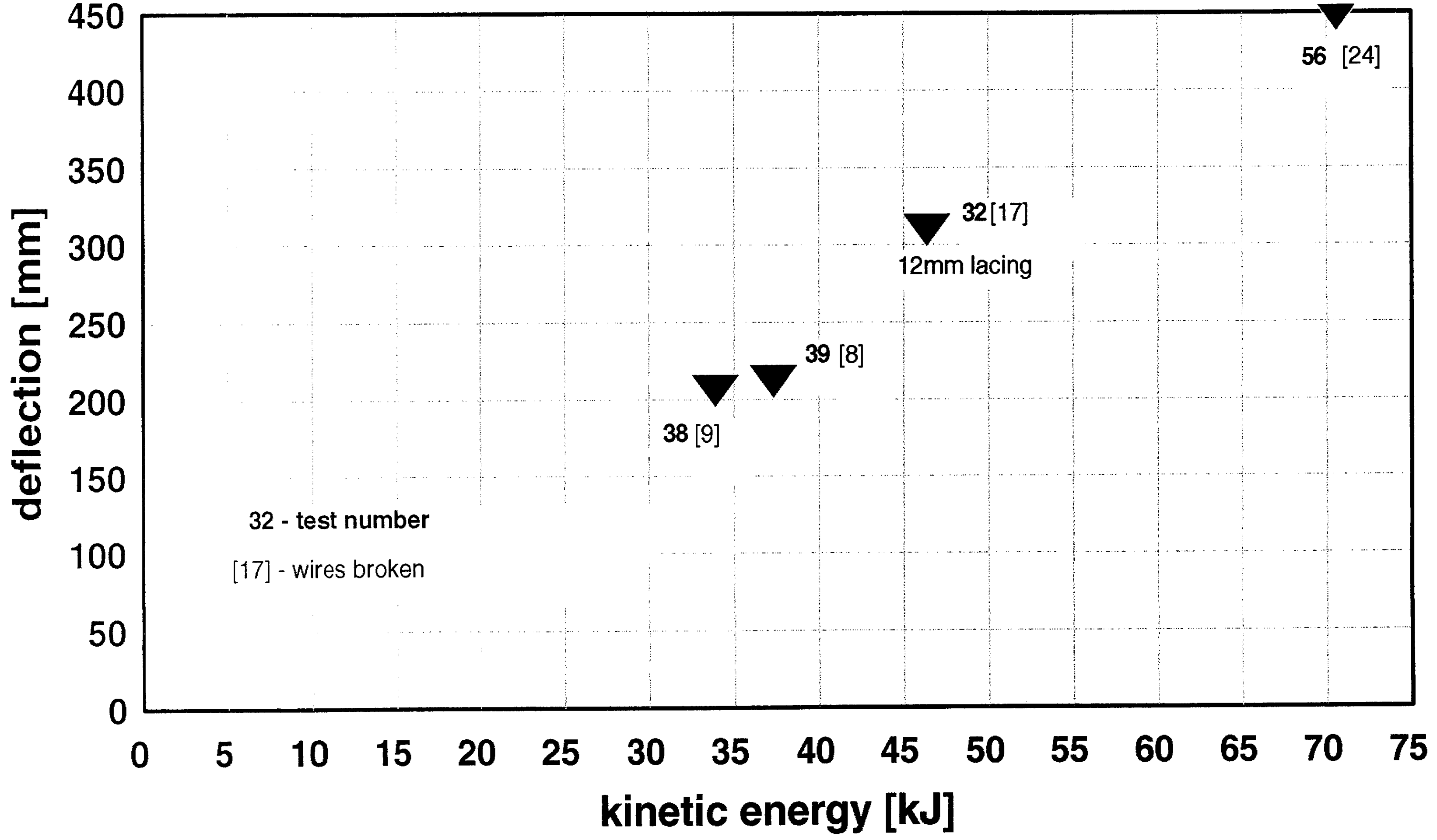
Series 3.3 - 100 x 3,2mm Diamond Mesh & 8mm Lacing



KIN. ENERGY vs DEFLECTION

Fig. 13

Series 4.1 - 100 x 3,5mm Weld Mesh & 10mm Lacing



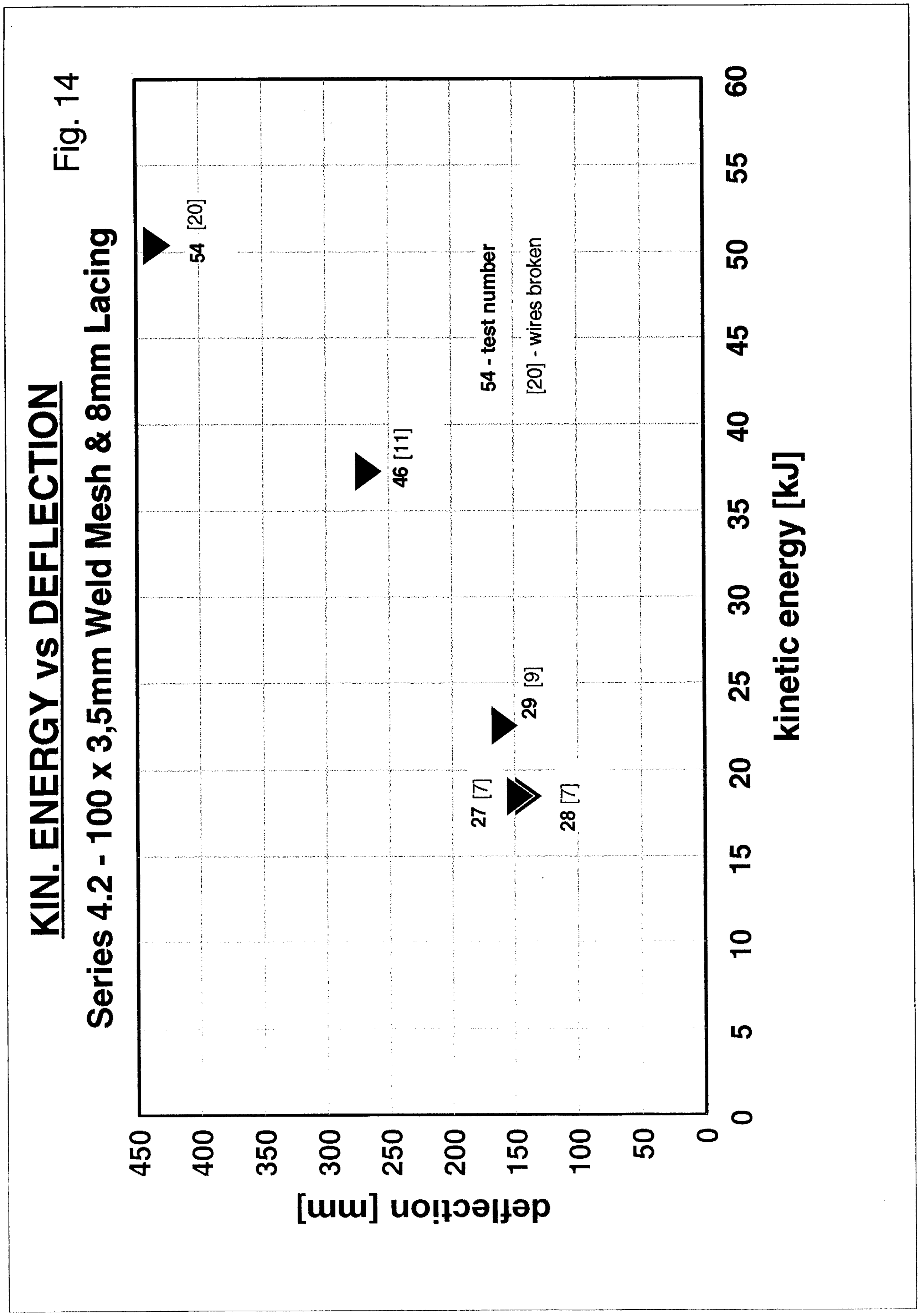
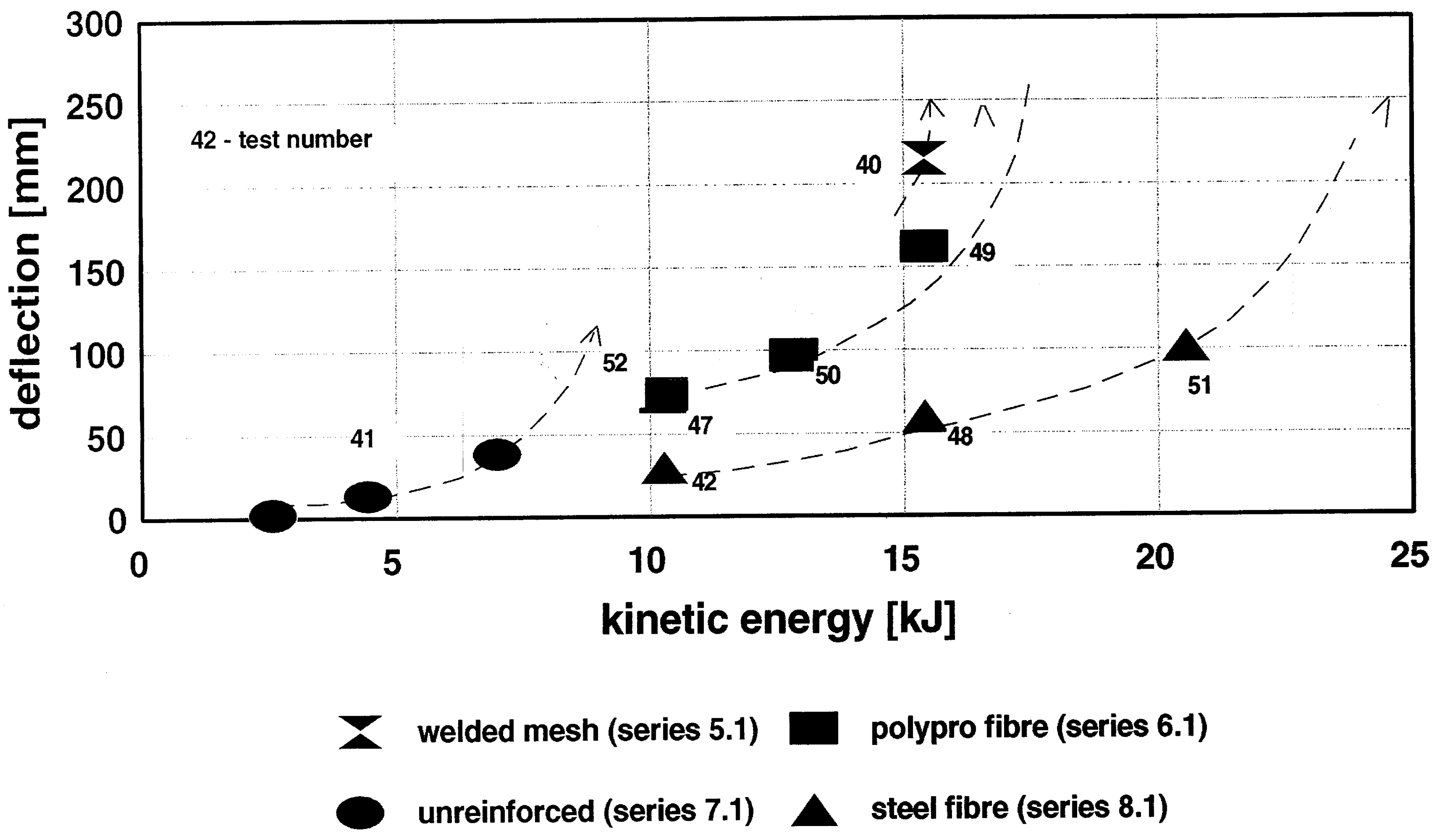

KIN. ENERGY vs DEFLECTION
Series 4.2 - 100 x 3,5mm Weld Mesh & 8mm Lacing
deflection [mm]
450
400
350
300
250
200
150
100
50
0
kinetic energy [kJ]
0
5
10
15
20
25
30
35
40
45
50
55
60
54 [20]
46 [11]
29 [9]
27 [7]
28 [7]
54 - test number
[20] - wires broken

Fig. 14

KIN. ENERGY vs DEFLECTION

Shotcrete

Fig. 15



RELATIONSHIP OF NUMBER OF BROKEN BLOCKS TO ENERGY OF IMPULSE

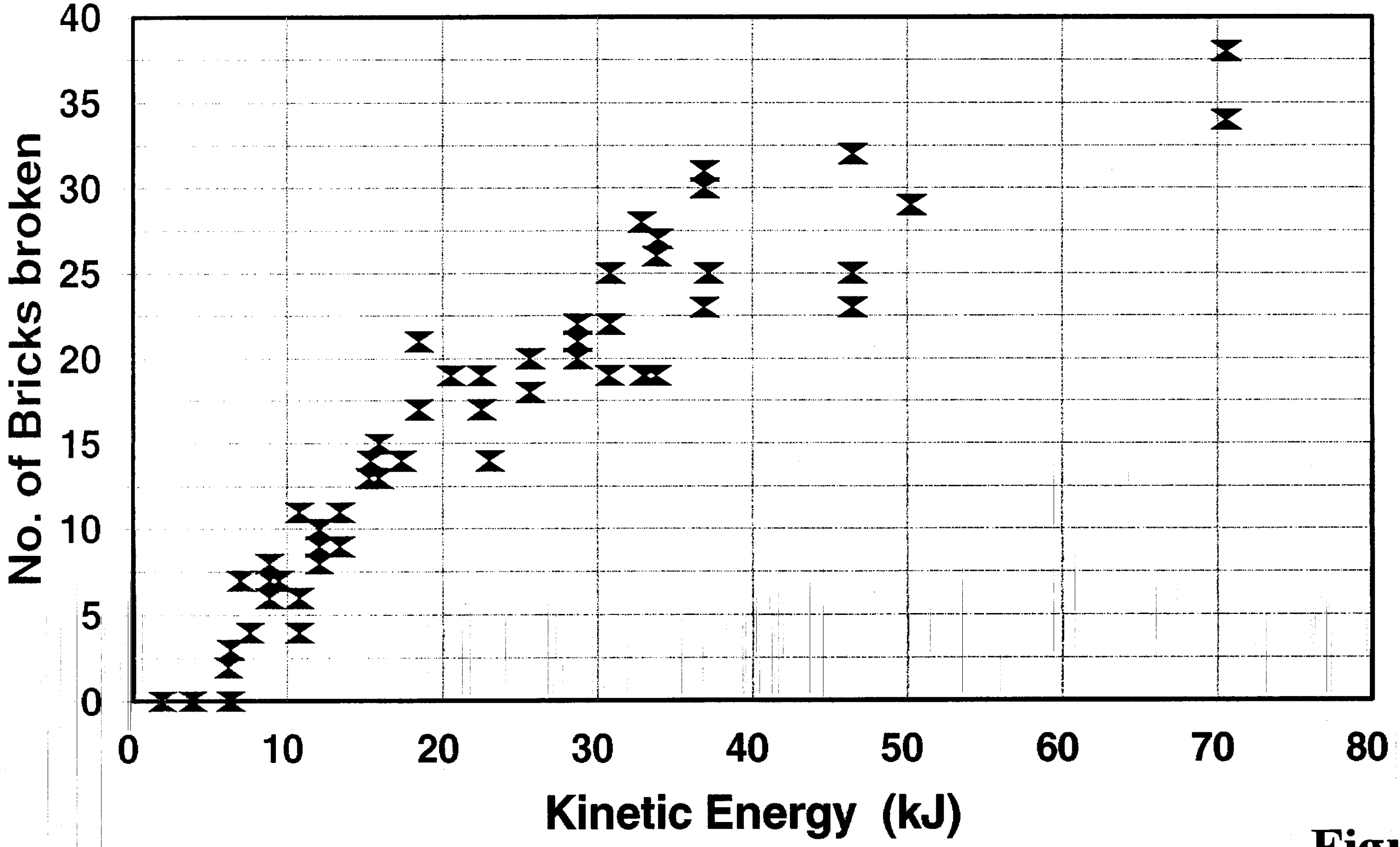


Figure 16

of the overall reproducibility and reliability of the test procedure.

Series No.	Table No.	Fig. No.	Element combination and dimension mm	Number of Tests	Energy Range kJ
1.2	B1	6	100x3,5 weld mesh	5	1,3 to 8,9
1.3	B2	7	100x4,0 weld mesh	4	7,0 to 8,9
2.1	B3	8	100x3,2 diamond mesh	4	6,4 to 12,1
2.2	B4	9	75x3,2 diamond mesh	5	9,6 to 15,9
2.3	B5	10	100x4,0 diamond mesh	4	10,8 to 15,9
3.1	B6	11	75x3,2 diamond+12mm lacing	2	33 and 46,5
3.2	B7	11	100x3,2 diamond 12mm lacing	4	33 to 70,6
3.3	B8	12	100x3,2 diamond+8mm lacing	9	22,6 to 37,3
4.1	B9	13	100x3,5 weld mesh +10mm lacing and 12mm lacing	4	33,9 to 70,6
4.2	B10	14	100x3,5 weld mesh +8mm yielding lacing	5	18,5 to 50,5
5.1	B11	15	shotcrete: mesh reinforced	1	15,4
6.1	B12	15	shotcrete: polypro-reinforced	4	10,3 to 15,4
7.1	B13	15	shotcrete : un-reinforced	1	6,1 (total for 3 impulses)
8.1	B14	15	shotcrete : 30 mm Dramix	3	10,3 to 20,6

Table 1: Summary of test series

4 SPECIFIC RESULTS AND PRACTICAL IMPLICATIONS

The composite plot in Figure 5 of all the observations confirms, for all types of cladding, the expected tendency that increased energy delivered by the impulsive load produces greater deflection of the test panel. The trend for greater damage to the whole test assembly in terms of the number of broken wires in the cladding and broken bricks in the "rock layers" behind the mesh is also clearly evident.

The relatively tight clustering of data points around this trend line (particularly evident in Figures 13 and 14) demonstrates the inherent reliability and reproducibility of the test method.

Together with the overall impressions gained during the whole programme, these observations in particular, support the contention that the test procedure gave consistent, reliable and realistic results that allow valid comparison of the *relative* capabilities of various forms of the cladding and other elements of containment support.

On this basis, the relative capabilities of the several types of support are best compared by reference to the individual series plots of deflection versus kinetic energy as presented in Figures 6 to 15.

4.1 Wire mesh and mesh and lacing containment support

4.1.1 Series 1.2 : 100mm aperture x 3,5mm diameter weld mesh

Figure No. 6 Table B1

At values of deflection of as little as 65 mm, resulting from impulses of as little as 3,5 kJ, individual wires broke. Without exception the wires broke near the square domed 6mm face-plates. Detail of this mode of failure is shown in photo 5. ***It was very apparent that the sharp "cropped" edges of standard support washers or face-plates are very detrimental to the performance of mesh support.***

Although no unravelling occurred, about 9 kJ produced such serious damage around the 4 points of suspension with existing bearing plates, that it was evident that:

The upper limit of performance capability of 100 x 3,2 mm thick black weldmesh is 9 kJ.

The practical implications of this limitation are that it is not worthwhile in terms of cost and effort to use weldmesh of 100 mm aperture, without lacing, if it is to be secured with existing square domed face-plates.

4.1.2 Series 1.3 : 100mm aperture, 4,0mm diameter weld mesh

Figure No. 7 Table B2

Results with 4,0 mm diameter wire were very similar to those with 3,2 mm wire in regard to the number of wires broken under the face-plates. Although the larger diameter of strand should theoretically give some 50% increase in in-plane strength, the limitation of face-plate "guillotining" became apparent at only slightly increased energy input, and the same practical implication applies as in the case of the lighter mesh.

The upper limit of performance capability is thus 10 kJ.

4.1.3 Series 2.1 : 100mm aperture, 3,2mm diameter diamond mesh

Figure No. 8 Table B3

The greater flexibility of diamond mesh that is inherent in its method of construction together with the lower tensile strength of the wire ensures that considerably more deflection takes place for equivalent impulsive load than occurs with weld mesh ("black" wire has a minimum UTS of 485 MPA, while the galvanised wire used in diamond mesh has a minimum UTS of 250 MPA). For the same reason, wires do not break until three times as much deflection has occurred. However, when even a single wire breaks, unravelling tends to occur. As was evident in test 7 (photo 6) when 5 bricks spilled through the gap caused by the failure of a single wire, this behaviour imposes a severe limitation on the usefulness of this type of fabric in the absence of lacing. As in series 1.2 and 1.3 the sharp edges of the standard washer have a serious detrimental effect.

The upper limit of capability is 11 kJ.

4.1.4 Series 2.2 : 75mm aperture, 3,2mm diameter diamond mesh

Figure No. 9 Table B4

Exactly the same trend as in series 2.1 of increased energy causing proportionately increased deflection, is evident here. Because of the greater number of wires per unit area, the energy levels are increased and deflection decreased compared with 100 x 3,2 diamond mesh, before serious damage results. All the other limitations and reservations mentioned before are applicable in this case as well. Photo 7 shows the appearance of this mesh after 16 kJ of energy caused 273 mm of deflection.

4.1.5 Series 2.3 : 100mm aperture, 4,0mm diameter diamond mesh

Figure No. 10 Table B5

The impulse load versus central deflection characteristic, is the same as for the previous series. No wires were broken by the highest load tested - see photo 8. Because of the slightly greater (17%) mass of wire per linear metre of mesh, it could be expected that the performance limit would be somewhat greater. This expectation was not tested and the maximum value of energy absorption of the heavy mesh by itself was not determined. It was considered more important to examine the effect of lacing, which is almost invariably used in practice to "back-up" the mesh, on the total capability of tunnel cladding.

The upper limit of capability is expected to be about 18 kJ.

4.1.6 Series 3.1 and 3.2 : 75 mm and 100 mm aperture, 3,2 diameter diamond mesh with destranded lacing

Figure No. 11 Tables B6, B7

For economic reasons, the preferred form of lacing on most mines is destranded old winding rope. A supply was obtained from the standard stock of a large gold mine.

The destranded lacing (12 mm, 118 kN strength) has a slight residual helix shape which is not pulled straight under the low tensions (< 10 kN) which can be applied in practice. The lacing is covered to a greater or lesser extent in rope dressing. The helix gives the lacing an intrinsic yield ability which is small but significant. Because of difficulties in clamping the lubricated lacing adequately, tests 33 and 34 failed when the lacing slipped free from the "boundary condition" stay wires.

At high values of deflection, it was evident that it was the lacing that provided the main resistance or energy absorbing capability, particularly when unravelling of mesh wires allowed the simulated rock to spill out. Photo 9 shows how unravelling of the 100 mm aperture mesh occurred in test 37 after 273 mm deflection resulted from 34 kJ of impulse. The 75 mm mesh was able to accommodate 243 mm deflection with no unravelling, at the same level of energy input.

The fact that it was the inadequacy of the mesh spanning the 0,71 m "window" between lacing strands that limits the energy absorption and not the lacing itself, was dramatically demonstrated by test 55. Improved connectors ensured that the 12 mm diameter lacing, without slipping, survived 71 kJ of impulse. However, the mesh unravelled and spilt a total of 10 concrete blocks from the four quadrants - photo 10.

The upper limit of capability of 100 mm x 3,2 diamond mesh is about 32 kJ

and that of 75 mm mesh probably 35 kJ when used with 12mm diameter destranded hoist-rope lacing.

4.1.7 Series 3.3 : 100mm aperture, 3,2mm diameter diamond mesh with 8 mm diameter lacing

Figure No. 12 Table B8

In practice destranded lacing of a significantly smaller diameter than was tested in series 3.1 and 3.2 is often used. Sometimes flexible (6 x 19 construction) wire rope of diameter as small as 8 mm (38 kN UTS) has been employed. It was therefore of some practical interest to determine the dynamic capabilities of such material.

When 8 mm flexible rope lacing was stretched tautly, failure of one or both diagonal strands occurred readily, usually at the sharp edged standard domed face-plates, but sometimes also at the central cross-over position - see photo 11.

The upper limit of capability of this system is about 20 kJ

It appeared possible that extending the strain limit before failure of the lacing, would improve the containment capability considerably. By introducing a single loop in each diagonal, extra length was incorporated into the lacing. Crosby clamps were used to provide resistance against the loop straightening out too readily. Photo 12 shows an example of this yielding device.

By controlling the torque applied to the nuts of the Crosby clamps it was possible to absorb high values of impulse energy up to 37kJ, without losing overall stability of the support system. Breaking of lacing was prevented and damage to the mesh was contained to a substantial degree. However, unacceptably high values of deflection occurred and unravelling of the diamond mesh could still occur and allow the "rock" to spill through. In test 44 for example, 200 mm of controlled slip on one diagonal of lacing avoided failure of the 8 mm flexible rope lacing but 232 mm central deflection occurred which allowed mesh to unravel and spill 3 bricks - see photo 13. When slip occurred too easily as in test 43 for example, failure of the lacing was not prevented, leading to total collapse of the support system - see photo 14.

In test 53, the yielding device and the lacing pattern appear to have been satisfactorily configured but the unravelling tendency of the diamond mesh led to comprehensive failure of the overall containment of the system - see photo 16 (a) and (b).

In test 45, yielding was inhibited at the connector, the lacing consequently failed, the diamond mesh unravelled and complete collapse of the containment followed - see photo 15.

Ingenuity and care is necessary to ensure the correct amount of slip, so this approach is not practicable at the present time. However, it is considered to be sufficiently promising to warrant further work.

The upper limit of capability of 100 x 3,2 diamond mesh with light *yielding* lacing is 30 kJ.

4.1.8 Series 4.1 : 100mm aperture, 3,5 mm diameter weld mesh with 10 mm and 12 mm lacing

Figure No 13 Table B9

Above the energy threshold beyond which the use of lacing becomes essential, the tendency for the wires of weld mesh to break around the bearing plates becomes relatively unimportant in the overall stability. The fact that fracture of wires or failure of welds does not occur elsewhere and the weld mesh does not **unravel**, means that the "rock" is retained and integrity is maintained. In this respect weld mesh is significantly less vulnerable than diamond mesh.

However, the need for improved coupling or connections between the lacing and the rockbolts or other tendons becomes obvious. It is immediately apparent that **standard washers or face-plates cannot be made to perform this function adequately**. "Eared" lacing plates are commercially available which, as far as protection of the lacing is concerned, are probably quite adequate for all but the most severe rockbursts. The problem of sharp cropped edges of the plate itself causing damage to the mesh, still exists - see photo 17.

To prevent this "guillotining" effect from imposing a spurious limit to the support capability of the 10 mm lacing back-up, a simple improved method of connector was devised. Using these with semi-taut 10 mm lacing (59 kN UTS) in test 39, enabled deflection to be limited to just over 200 mm after an energy impulse of 37 kJ - see photo 18.

The upper limit of support capability of 100 x 3,5 weldmesh with 10 mm flexible rope lacing is probably at least 38 kJ.

In test 32, which was subjected to 46 kJ, many wires broke around the face plates but the mesh remained intact across the "windows" between the lacing and no bricks spilled out - see photo 19. In test 56, an impulse of 70 kJ caused massive damage to the weld mesh effectively destroying the containment even though the 12 mm lacing survived, and the 3 link chain link connectors were totally unscathed. Photos 20 and 21 give an indication of the violence and damage associated with this level of energy input.

The upper limit of support capability of 100 x 3,5 weld mesh with 12 mm lacing is thus about 50 kJ.

4.1.9 Series 4.2: 100mm aperture, 3,5 mm diameter weld mesh with 8 mm yielding lacing

Figure No 14 Table B10

Using the same care to ensure yielding of the lacing, and connectors that did not damage wire mesh or lacing, it was evident that similar improved performance could be achieved with lacing of even lower strength than that used in Series 4.1 (viz. 38 kN for 8 mm compared with 59 kN for 10 mm rope of 6 x 19 construction).

Although only one half brick spilled out at one suspension point in test 54, two wires did break at the centre - see photo 22 - so 50 kJ was beyond the capability of this type of containment.

The upper limit of support capability is thus probably about 45 kJ.

4.2 Shotcrete Containment Support

A form of containment frequently used in the support of larger service excavations is gunite or shotcrete applied over weld mesh. To gain some idea of its dynamic capability compared with flexible mesh cladding, a single test was performed on a shotcrete slab of nominal 100 mm thickness

The use of "dispersed reinforcement" in the form of fibres has been advocated, and is being actively investigated, as a way to make shotcrete a possible alternative form of containment that would be more easily and effectively applied to a tunnel surface than steel mesh.

Performance properties derived from the test on the weld mesh-reinforced shotcrete slab would then also form a basis of comparison for properties determined from tests on fibre-reinforced shotcrete slabs.

4.2.1 Series 5.1 : Shotcrete reinforced with 100mm aperture, 4 mm diameter weld mesh

Figure No 15 Table B11

A single impulsive load of 15 kJ was imparted to a slab of 1,6 x 1,6 m size suspended in the same way under similar edge constraints as was done with the mesh containment.

Two main cracks orientated N-S and E-W, together with several minor radiating cracks, formed at impact and the slab incurred 215mm of displacement at its centre - see photo 23.

All the wires traversing the two main cracks were broken. The test piece was comprehensively destroyed although it did not collapse because of the edge constraints.

The upper limit of support capability is estimated to be 10 kJ.

4.2.2 Series 6.1 : Shotcrete with 50 mm long monofilament polypropylene fibres

Figure No 15 Table B12

Four slabs were produced in the same manner as for Series 5.1 but with 0,5% (by mass) of 0,9 mm diameter monofilament fibres 50 mm long as dispersed fibre reinforcement in place of the weld mesh. Photo 24 gives an indication of the fibre concentration and uniformity of its distribution. Input energies ranged from 10,3 to 15,4 kJ producing similar crack patterns on each slab - see Figures 17 and 18. The crack pattern appeared to be fully developed almost immediately after the impact before significant deformation occurred - see photo 25.

Figure 15 illustrates well how deflection increased strongly and progressively with increased energy input, clearly approaching asymptotically to the level of complete destruction shortly after 15 kJ is reached.

Once substantial cracks had been produced, a second, usually much smaller, impulse was sufficient to destroy the slab in each case - see photo 26. This suggested that a tunnel lining might be able to survive a moderate rockburst but would thereafter, if it had been significantly cracked, not present much resistance to repeated seismicity.

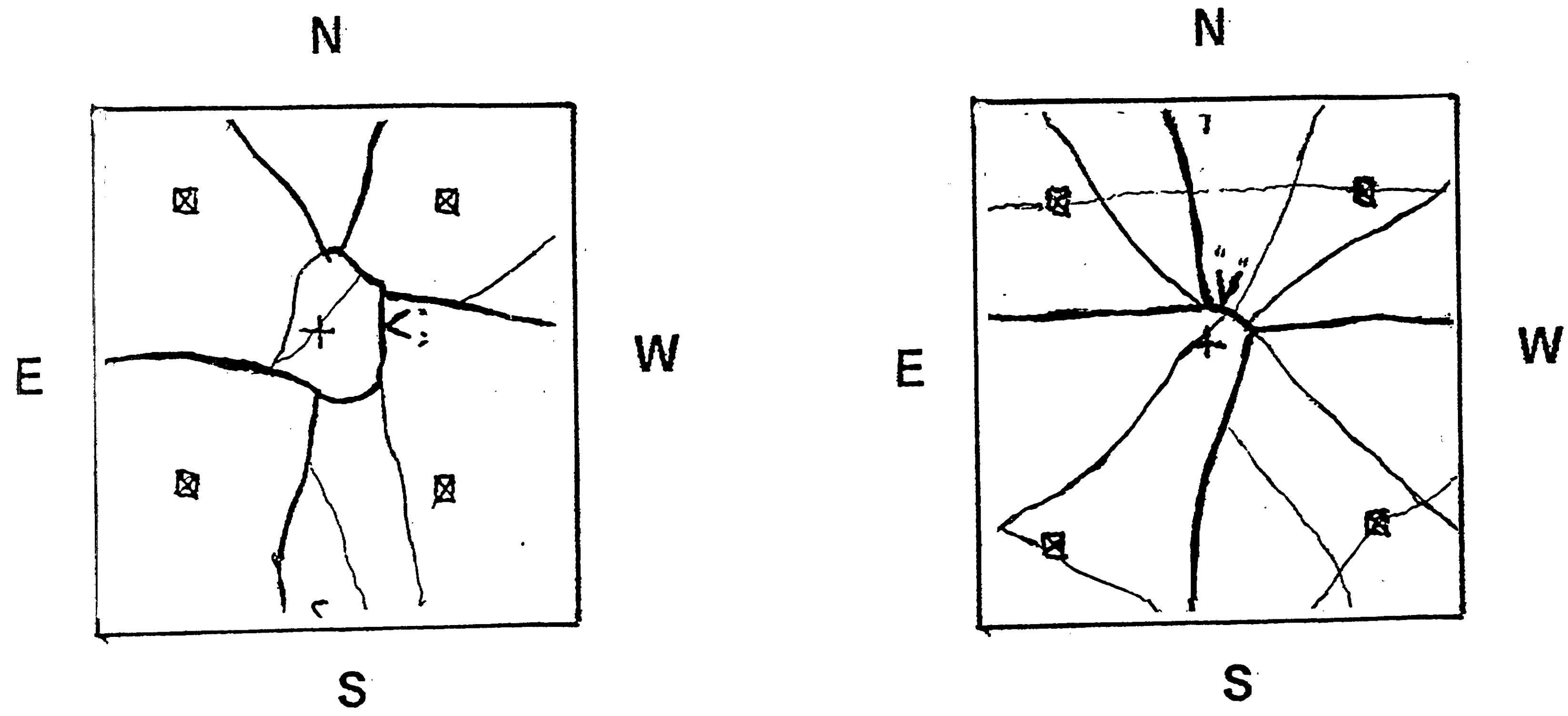
The upper limit of support capability is 15 kJ.

4.2.3 Series 7.1 : Unreinforced shotcrete

Figure No 15 Table B13

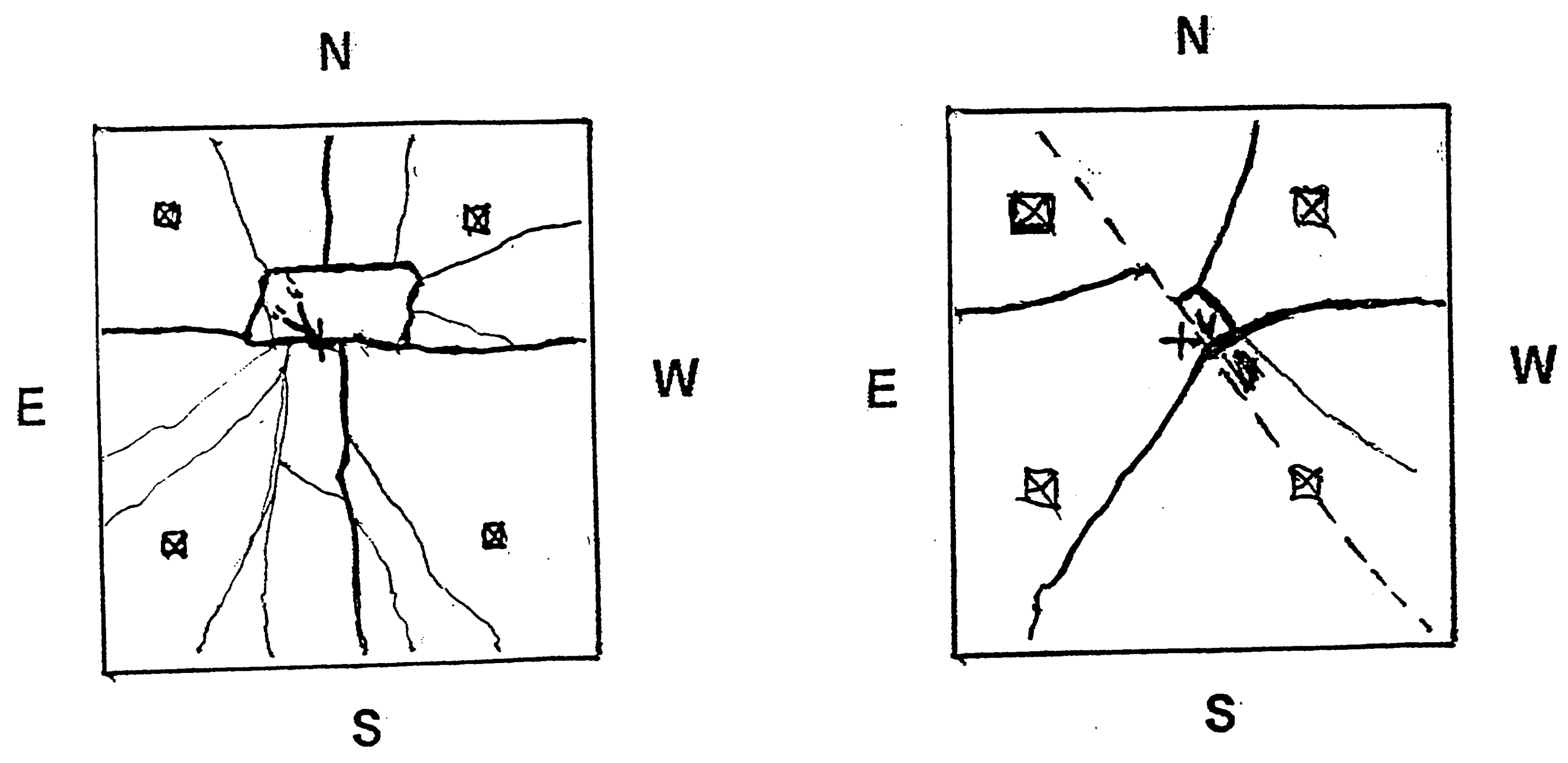
In the single test that was performed on unreinforced shotcrete the slab was subjected to three small, consecutive energy inputs. The progression to complete destruction is clearly evident on Figure 15 and the crack configuration is shown in Figure 19. The development of the cracks is shown in photo 27.

The upper limit of support capability of unreinforced shotcrete is probably less than 5 kJ.


Test No. 50. 50 mm Poloypropylene

Test No. 49. 50 mm Polypropylene

Figure 17: Shotcrete slab - crack configuration



Test No. 51. 30 mm Dramix

Test No. 52. 50 mm Polypropylene

Figure 18: Shotcrete slab - crack configuration

Test No. 41. No reinforcing

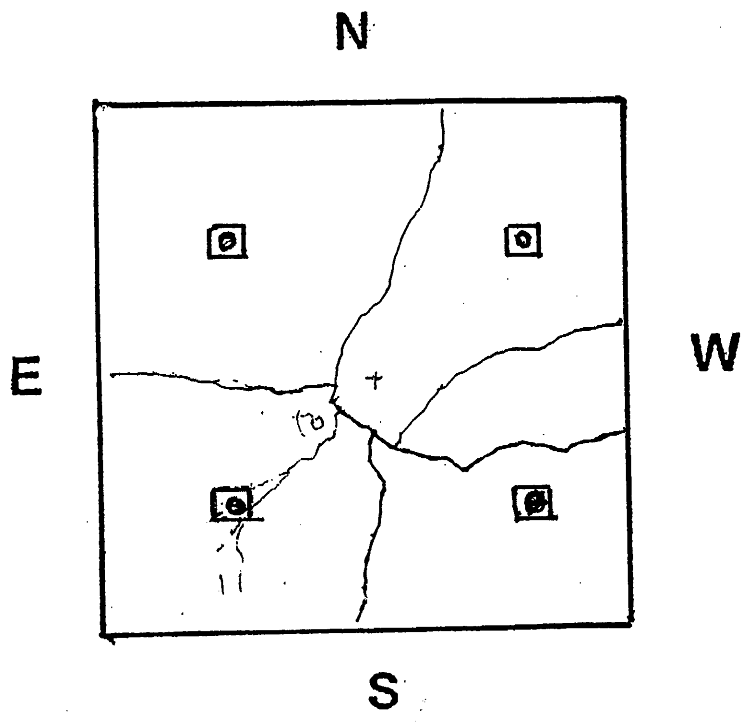


Figure 19: Shotcrete slab - crack configuration

4.2.4 Series 8.1: Shotcrete with 30 mm Dramix steel fibre

Figure No 15 Table B14

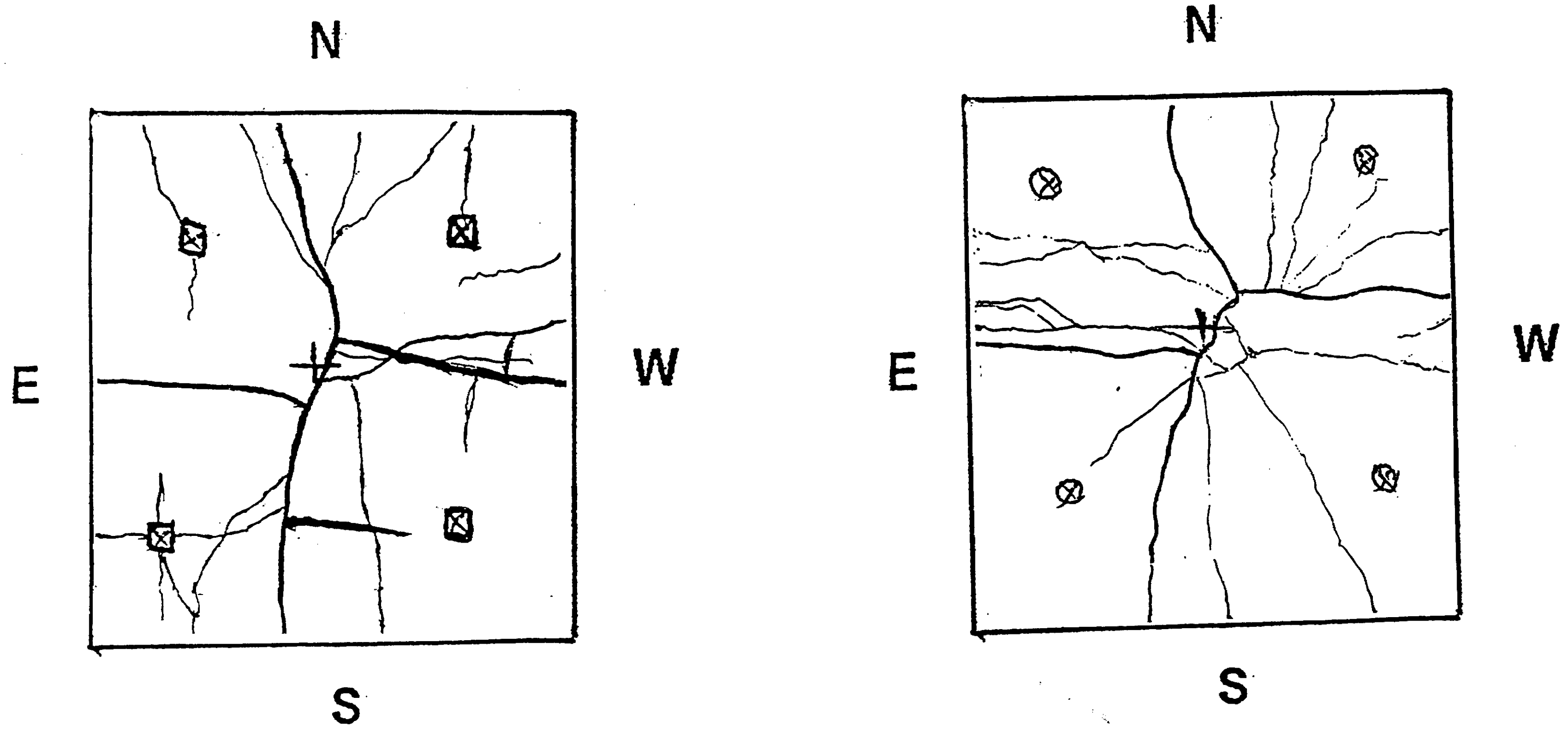
Three slabs containing 2,75% (by mass) of 30 mm long Dramix fibre were produced and tested in the same manner with the same shotcrete mix as before. Input energies ranged from 10,3 to 20,6 kJ. The same tendency for increased deflection with increased input energy was evident as with the polypropylene fibre, but the amount of deflection was considerably less and the rate of increase was slower. At lower energies, repeated impulses could be sustained with the main cracks opening further each time - see photo 28. Figures 18 and 20 show the crack configurations. Photo 29 shows that Dramix fibres did not break but tended to straighten at the "staple" end and pull out of the matrix.

This suggests that a rockburst-prone tunnel could survive additional smaller rockbursts after an initial moderate event had caused appreciable cracking, **provided that no corrosion of the steel fibres had occurred.**

The upper limit of performance capabilities of steel-fibre reinforced shotcrete against a first dynamic impulse is 20 kJ.

5 OBSERVATIONS OF DISPLACEMENT VELOCITY

The most obvious feature of rockburst damage that distinguishes it from quasi-static stress damage is the suddenness of the event. No actual measurements have been made of the kinetics of tunnel wall-rock movement during a rockburst. Estimates are based on inferences drawn from post-event observations. Values of velocity of displacement of several metres per second are frequently quoted.



Test No. 48. 30 mm Dramix

Test No. 42. 30 mm Dramix

Figure 20: Shotcrete slab - crack configuration

The drop-weight dimensions chosen for this programme yielded impact velocities which ranged from 2 m/s to 8,4 m/s.

Underground observations sometimes suggest that the velocity transferred from the particle movement in the solid rock mass to the displaced rock, is considerably enhanced by reflection or other near-surface effects.

Similar impressions were gained in several of the tests in this programme when viewing the simple video record or studying the 'impact snapshot' eg. photos 13, photo 19.

As the simple video does not have sufficient time resolution to permit estimation of velocities, a special high speed video study was made of test no. 34.

The graphical result of this analysis is shown in Figure 21. The dynamic nature of the phenomenon is illustrated in Figure 22. Note that this sequence is an excerpt from the simple video which, although unable to provide more than 50 scans per second or good resolutions of moving objects, has better sharpness of static images.

The analysis showed that, for a period of 40 ms or so, the test surface was moving up to twice as fast as the drop weight (the impulse "driver"). It even appeared that, for a fraction of this short time period, the velocity of the driven mass was appreciably greater than the maximum velocity of the drop-weight just before impact.

In this respect then, the test methodology would appear also to simulate, qualitatively at least, the characteristics of a real rockburst.

6 CONCLUSIONS

As the number of completed tests increased it became increasingly evident that the test methodology was reliable, reproducible and relevant. Observations and analyses such

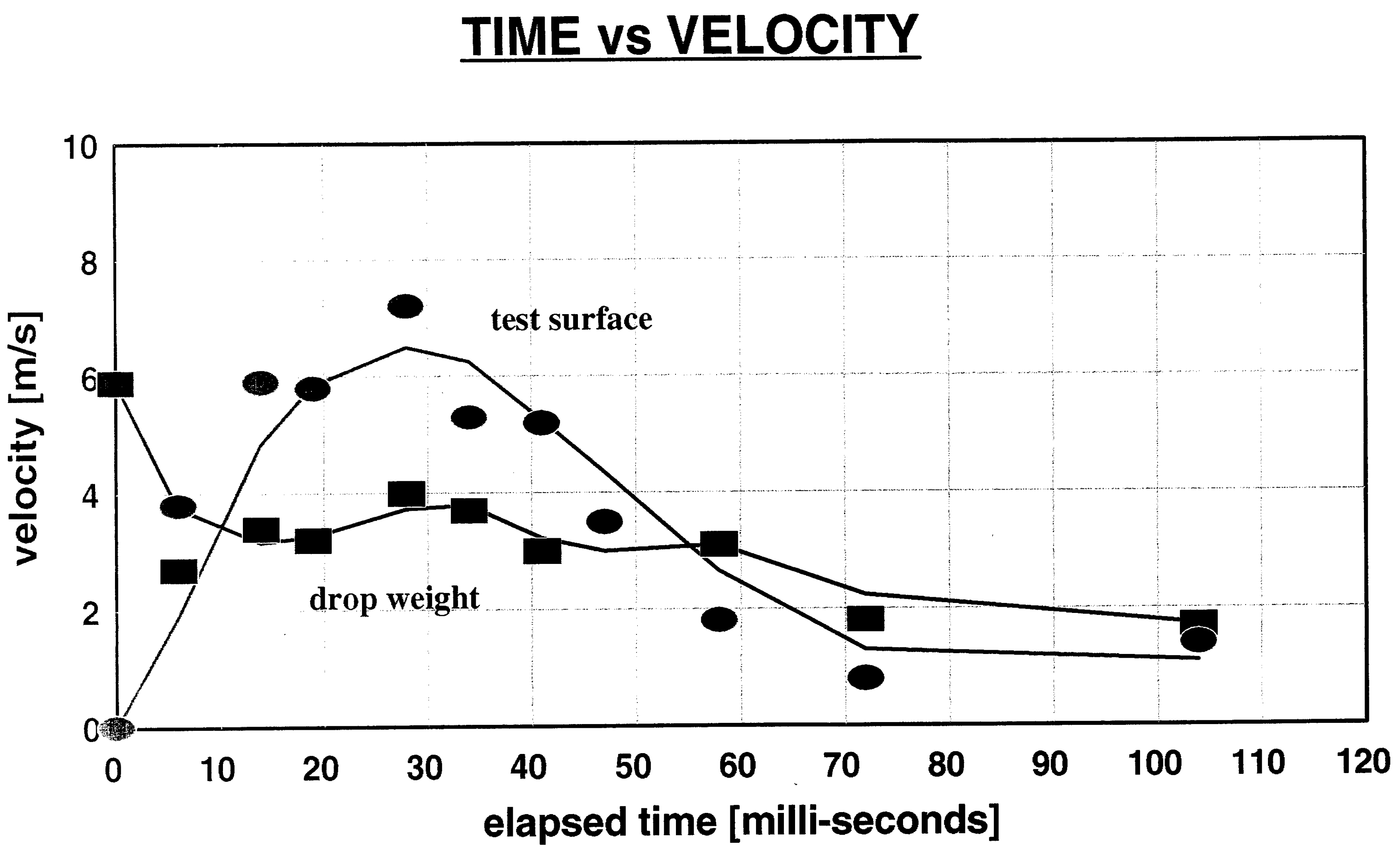
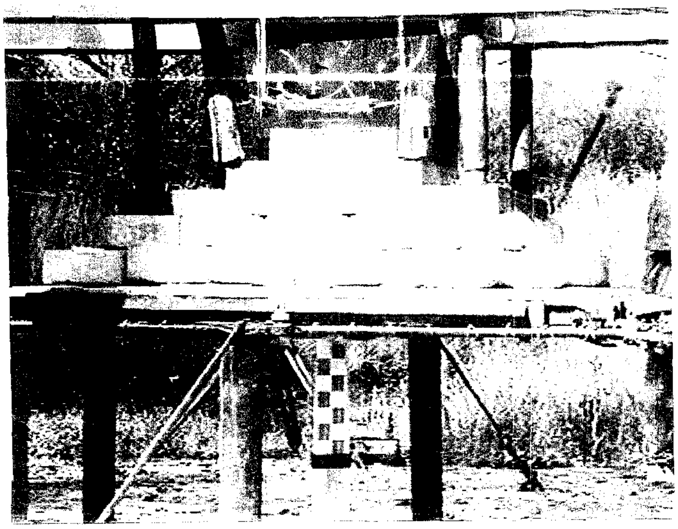
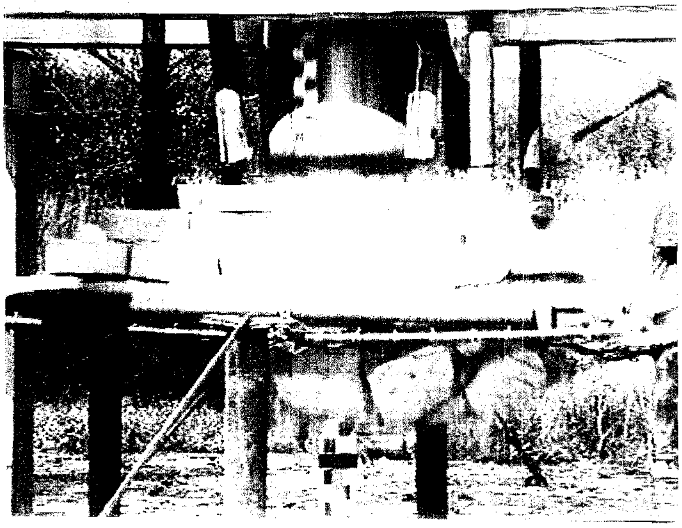


Figure 21: Velocity changes with time - Test 34



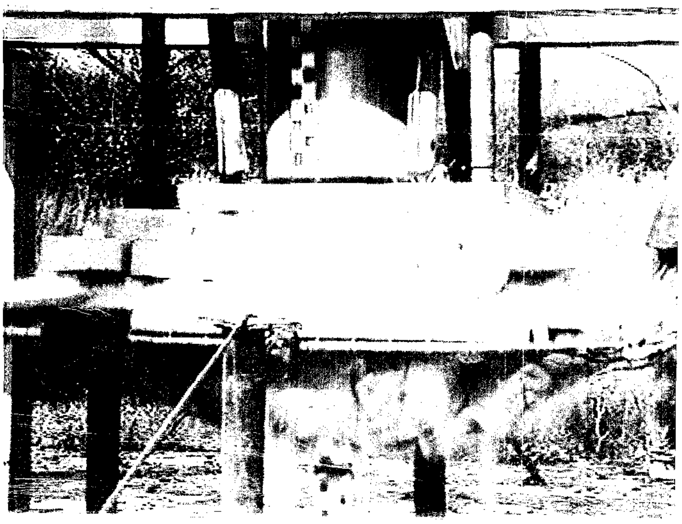
Time: t_0

Drop-weight (outlined in white) a few milli-seconds away from impact



Time: $t_0 + 0,06s$

60 milli-seconds later, 250 mm displacement has occurred



Time : $t_0 + 0,10$ s

Concrete blocks are breaking through diamond mesh

Figure 22: Video sequence of Test 34

as those discussed in Section 5, also lent assurance to the belief that the results were qualitatively realistic - the behaviour and damage observed in the tests was visually very similar to that observed under real operating conditions. The following general conclusions and deductions can accordingly be made with a considerable degree of confidence:

- the performance limits of all elements of a mesh/lacing containment system should be **balanced,** in a way that is compatible with the capability of the tendon retaining elements;
- the lacing is the most important single element in the containment component of a tunnel support system subjected to significant dynamic loading;
- lacing can, however, be too strong (and hard) for other presently-used elements e.g. de-stranded hoist rope strands of greater than 14 mm diameter could cause failure of the tendon connections e.g. could fracture shepherds' crooks loops;
- some yieldability of the lacing is necessary and over-tensioning (in excess of 10 kN) is probably detrimental in that it may increase the likelihood of failure of the smaller diameter ropes or strands or of connecting elements;
- bearing plates formed by conventional punching or guillotining of 6 mm mild steel plates are not compatible with mesh. Diamond mesh in particular is vulnerable in this respect. The standard face-plates could, and should, be easily improved;
- most elements of the containment system can be significantly improved;
- a containment system utilizing presently available mesh and lacing with improved connectors and available yielding tendons **spaced at 1 m centres**, can be expected to withstand a "once-off" rockburst of 50 kJ/m^2 intensity. This would be considered a **severe** event.

Only if the same 1,0 m limitation on the spacing between tendons is observed, can the quantitative values in Section 4 - Results - be used as guide-lines in the design of support systems.

Recognizing strictly that it is within the context of 1,0 m spacing between rockbolts, the following more specific conclusions can be drawn:

- without lacing, diamond mesh is superior to weld mesh as the containment element under low energy dynamic conditions up to 15 kJ/m^2;
- with appropriate lacing, weld mesh is better than diamond mesh at higher energy levels as it is less prone to unravelling or splitting and so allowing the spill-out of rock fragments;
- present tunnel support practice of overlapping the edges of a strip or panel of mesh is inadequate as it provides an opportunity for rock fragments to spill through in the same way as unravelling of diamond mesh does;
- the yieldability of weldmesh can be improved without major difficulty. Together with the more easily installed and efficient zig-zag lacing pattern and chain-link connectors, such improved weldmesh could, it is believed, contain the damage from a 70 kJ/m^2 event which would probably represent a major rockburst.
- it is very difficult, even conceptually, to visualize how diamond mesh could be modified to eliminate the problem of unravelling.

Suitably reinforced shotcrete has the potential, as containment, to withstand dynamic loading to some extent at least. Large aperture weldmesh, which is the only one of the commonly used mesh types that is suitable for use as discrete reinforcement with shotcrete has a somewhat limited capability for accommodating large deformations. It would not be suitable for use as tunnel cladding in rockburst-prone areas.

Dispersed reinforcement, as provided by suitable steel or polymer fibres, appears to be better suited as cladding or containment in tunnels subject to seismic risk. Preliminary indications are that fibre-reinforced shotcrete could be used together with suitable yielding tendon support at 1 unit/m^2 density in areas where low-intensity rockbursts might occur. Where impulses of about 10 kJ/m^2 occur a fibre-reinforced shotcrete layer would probably provide adequate cladding. However it would be necessary to recognize that if an event should create significant cracks, corrosion could severely impair the longer term strength of the cladding where steel fibres had been used as the dispersed reinforcement.

In the case of polypropylene fibres, the ability of the shotcrete cladding to contain succeeding rockbursts may be limited.

7 DESIGN RECOMMENDATIONS

There is no doubt that the GAP 221 project has yielded a considerable amount of new knowledge and understanding of the performance capabilities of the various elements that make up a containment system for tunnel support under rockburst and high stress conditions. The consideration of design recommendations given below should be seen as indicative. Tests have only been carried out for one rockbolt spacing.

7.1 Mesh and Lacing

It could be claimed that **(for a 1,0 m bolt spacing system)** the data obtained from the research could be used, with only a relatively small amount of intuitive input, for the design of a tunnel support system. The following points outline the scope of conditions that might be catered for by a responsible, albeit perhaps a somewhat conservative, design:

i) **For areas of relatively low-intensity seismic risk - 15 kJ/m^2**

100 x 4,0 mm diamond mesh over 16 mm diameter yielding bolts with modified 6 mm thick square domed face-plates of minimum 150 mm side dimension.

ii) **For areas of moderate-intensity seismic risk - 30 kJ/m^2**

100 x 3,5 mm galvanized weld mesh over 20 mm diameter yielding bolts with "eared" face-plates (or 3-link chain-link connectors) and light zig-zag lacing (about 45 kN strength).

iii) For areas of high-intensity seismic risk - 60 kJ/m^2

100 x 3,5 mm galvanized **extensible** weld mesh over 22 mm diameter yielding bolts with 3-link chain-link connectors and 12 mm diameter (120 kN UTS) lacing in a zig zag pattern.

By "extensible weld mesh" is meant weld mesh that has some in-built yield capacity greater than that of the standard weld meshes commonly used in the mining industry. Preliminary tests on some modified weld meshes have been carried out, not as part of the SIMRAC research programme, and have shown potential with regard to extensibility. Further development and testing are required before concrete design recommendations can be made which include such mesh.

7.2 Shotcrete as cladding

There is no doubt that the operation of installing mesh and lacing can be greatly improved with a consequent reduction in time and therefore exposure to dangerous conditions. Nevertheless it remains essentially a labour intensive manual operation.

The increasing depth of proposed mining, and the resulting increased imperative to provide support immediately behind the advancing tunnel face to ensure safety and stability, confronts the industry with an urgent need to explore the feasibility of developing shotcrete technology to the point where it could replace one or both of the mesh and lacing components.

The 9 tests comprising the four series 5.1 to 8.1 represent a first step in this endeavour.

The initial results are regarded as encouraging and sufficient to indicate that further work on fibre-reinforced shotcrete is both justified and essential, and that shotcrete could represent support that can provide conditions of safety comparable with those provided by the containment support currently used in the mines.

Early indications are that an overlay of lacing suitably connected to the yielding tendons (that remain as an essential element in the total support system) would be necessary in the seismic risk areas of moderate energy intensity to back-up a 75 mm thickness of fibre-reinforced shotcrete.

The problem of preventing corrosion or age-deterioration of the fibre-reinforcement will also have to be solved.

8 RECOMMENDATIONS FOR FURTHER RESEARCH

In order to extend the knowledge-base of reliably-determined performance characteristics of support elements to the stage where it can be confidently felt that the optimum design has been achieved for a wide spectrum of conditions, a considerable amount of further testing is necessary.

The most important areas which urgently require further investigation to contribute to safer and improved support are:

- the quantitative determination of the effect of varying the **spacing** between tendons;
- establishing the true extent of the dynamic deficiencies of **stiff,** fully-bonded tendons such as re-bar shepherds' crooks;
- determining the in-situ, dynamic yielding properties of **friction-anchored devices** such as split-sets and swellex;
- determining the actual yielding potential of fully-grouted cable and rope anchors;
- development and testing of improved, extensible mesh which has greater energy absorbing capabilities;

- exploring the feasibility of using fibre-reinforced shotcrete to replace mesh/lacing containment in areas of low-intensity seismic risk;

- exploring the feasibility of using light, yielding lacing over fibre-reinforced shotcrete particularly with increased spacing between tendons, to replace mesh and lacing in areas of moderate-intensity seismic risk;

- ascertaining the upper limit of energy intensity that can be effectively contained by a practicable support system using optimized and balanced individual elements of retention and containment.

APPENDIX A

SIMRAC RESEARCH PROPOSAL

SIMRAC 1

DEPARTMENT OF MINERAL AND ENERGY AFFAIRS
PROPOSAL FOR A PROJECT TO BE FUNDED IN TERMS OF THE MINERALS ACT
- CONFIDENTIAL -

DMEA REFERENCE NUMBER
GAP 221
(FOR OFFICE USE ONLY)

1. PROJECT SUMMARY

PROJECT TITLE : Testing of tunnel support: Dynamic load testing of rock support containment systems (eg wire mesh)

PROJECT LEADER : T R Stacey

ORGANIZATION : Steffen, Robertson and Kirsten

ADDRESS : P O Box 55291, NORTHLANDS, 2116

TELEPHONE : (011) 44 11143 TELEFAX : (011) 88 08086 TELEX :

PRIMARY OUTPUT[1] :

1. Capabilities of alternative containment systems under simulated rockburst conditions.
2. Design data for rockburst support.

HOW USED ?[2] : 1. Direct use in the design and implementation of rockburst support. 2. Capacity tests of commonly used rock containment support.

BY WHOM ?[3] :
1. Mines.
2. Support manufacturers.

CRITERIA FOR USE[4] : N/A

POTENTIAL IMPACT[5] : 1. Information to the mining industry on the performance of rock containment systems used.
2. Provision of valuable information for the development of improved support systems.
3. Improvement in the safety in mines.
4. Potential savings in support costs could be considerable.

FUNDING REQUIREMENTS (R 000's)	YEAR 1	YEAR 2	YEAR 3
TOTAL PROJECT COST	202 441	296 400	
TOTAL SUPPORT REQUESTED FROM SIMRAC	202 441	296 400	

DURATION (YY/MM) Two years from date of award

SIMRAC SUB-COMMITTEE : AU/PT ☒ COAL ☐ OTHER ☐ GENERIC ☐

2. PROJECT DETAILS

2.1 Primary Output[1]

1. Capacities and capabilities of alternative rock containment systems.
2. Information for rockburst support design specifications.
3. Design data for specific containment support elements and systems.

2.2 Other Outputs (deliverables)[6]

Data on performance of the alternative containment support will become available progressively in a preliminary form during the progress of the research project.

2.3 Enabling Outputs[7]

NO.	ENABLING OUTPUT	MILE-STONE DATE	MAN DAYS
1.	Test geometry definition	Month 1	10
2.	Design of test facility	Month 4	10
3.	Preparation of test facilities	Month 6	6
4.	Preliminary testing and evaluation	Month 7	5
5.	Modification of design of facility and modification of facility if required	Month 9	6
6.	Test programme. Results produced progressively over the testing period	Month 20	91
7.	Interpretation of results	Month 21	10
8.	Report preparation	Month 27	27

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2.4 Methodology[8]

NO. OF ENABLING OUTPUT	STEP NO.	METHODOLOGY TO BE USED TO ACCOMPLISH THE ENABLING OUTPUT (INDICATE STEPS/ACTIVITIES)
1	(i)	Conceptual design of tests
2	(i)	Design of reinforced concrete test facilities
3	(i)	Construction of test facility
4	(i)	Initial test
5	(i)	Conceptual modification of tests
	(ii)	Design of modified test facility
	(iii)	Construction modification
6	(i)	Test programme

Key Facilities and Procedures to be used in the Project

1. Impulsive loading of rock containment systems.
2. High speed photographic recording of tests.

3. FINANCIAL DETAILS[9]

3.1 Financial Summary

	R		
	YEAR 1	YEAR 2	YEAR 3
Project staff costs (from 3.2)	102 080	219 500	
Other costs:			
Operating costs (from 3.3)	5 500	10 500	
Capital & plant costs (from 3.4)	-	-	
Sub-contracted work (from 3.5)	70 000	30 000	
Value added tax*	24 861	36 400	
Total cost of project	202 441	296 400	
Less funding from other sources (from 3.6)	-	-	
Support requested from SIMRAC	202 441	296 400	

*Only for VAT registered concerns

3.2 Project Staff Costs

	MAN DAYS		
NAME AND DESIGNATION	YEAR 1	YEAR 2	YEAR 3
T R Stacey	10	10	
W D Ortlepp	17	44	
Engineer	28	44	
Draftsman	2	-	
Tracer	-	10	
TOTAL (R000s)	102 080	219 500	

3.3 Operating Costs (Running)

ACTIVITY/EQUIPMENT (Items above R10 000)	COST (R)		
	YEAR 1	YEAR 2	YEAR 3
Car travel	1 500	3 500	
Photocopies, photographs,			
videos, documentation, etc	3 000	6 000	
Other miscellaneous items	1 000	1 000	
TOTAL	5 500	10 500	

3.4 Capital and Plant Costs[10]

NONE

(i) ITEMS TO BE PURCHASED OR DEPRECIATED FOR MORE THAN R10 000 PER ITEM	COST (R000s)		
	YEAR 1	YEAR 2	YEAR 3
Other miscellaneous items			
TOTAL			

(ii) ITEMS TO BE MANUFACTURED WITH ASSEMBLED COST OF MORE THAN R10 000 INCLUDING MATERIAL AND LABOUR	COST (R000s)		
	YEAR 1	YEAR 2	YEAR 3
Other miscellaneous items			
TOTAL			
TOTAL (i) and (ii)			

3.5 Sub-contracted Work

SUB-CONTRACTOR	ACTIVITY	COST (R000s)		
		YEAR 1	YEAR 2	YEAR 3
Civil Contractor	Construction of test facilities	45 000		
Drilling Contractor	Drilling and installation of bolts	5 000	5 000	
Blastech	Blasting, Explosives, High speed photography	15 000	20 000	
Quarry / Other sites	Provision of facilities and services	5 000	5 000	
	TOTAL	70 000	30 000	

3.6 Other Funding

ORGANIZATION	NATURE OF SUPPORT/ COMMITMENT	AMOUNT (R000s)

4. MOTIVATION

(Provide a clear and quantified motivation or justification for the proposal, as well as the main conclusions of a literature survey and the findings of related local and interantional research. The motivation should include a synthesis of previous work in the project area, both locally and overseas, why the project is proposed, what the primary output will achieve and a cost benefit analysis, if applicable. Use continuation pages where necessary but in most cases it should be possible to clearly present the key data and arguments in the space provided.)

Recently a series of tests on rebar rockbolts and cone bolts has been completed using impulsive loading (simulated rockburst loading with the use of explosives). These tests have demonstrated graphically the ineffectiveness of conventional rebar elements in withstanding rockburst loading, and the success that the yielding cone bolts show in containing the "rockbursts" with no damage to the elements.

The tests have been specifically on the "retaining" portion of support systems. For a support system to be fully effective in rockburst situations, and maximise safety under such conditions, the support must also be able to "contain" rock material which is usually ejected with force in rockburst events. It is therefore necessary to test "containment" systems under impulsive loading.

The research proposal is for the impulsive load testing of the following containment configurations (note that cone bolts will be used in all cases as the retainment elements except where otherwise indicated):

- weldmesh
- weldmesh + shotcrete
- diamond mesh 1
- diamond mesh 2
- diamond mesh (n) + shotcrete
- diamond mesh (n) + lacing
- shepherds' crooks + diamond mesh + lacing (typical support as commonly used in mines, for comparison purposes)
- alternative face plates
- fibre-reinforced shotcrete

The results of the tests will provide valuable design information for future installation of rockburst support, and should indicate possibilities for more cost effective support.

TRS

5. CURRICULA VITAE OF PROJECT LEADER AND RESEARCH STAFF

5.1 Summary Information

Project Leader

NAME & INITIALS: T R Stacey AGE: 50

QUALIFICATIONS (eg. degree/diploma, issuing institution and date): BSc Eng (1965) MSc Eng (1968) University of Natal, DSc Eng (1973) Pretoria University, DIC Engng Geol (1974), Imperial College, London University

SPECIAL AWARDS: (See CV)

Principal Project Team Members

NAME & INITIALS: W D Ortlepp AGE: 62

QUALIFICATIONS (eg. degree/diploma, issuing institution and date): BSc Eng (Wits) 1952 M.Eng Montreal 1957

SPECIAL AWARDS: Chamber of Mines Gold Medal and Scholarship

NAME & INITIALS: AGE:

QUALIFICATIONS (eg. degree/diploma, issuing institution and date):

SPECIAL AWARDS:

NAME & INITIALS: AGE:

QUALIFICATIONS (eg. degree/diploma, issuing institution and date):

SPECIAL AWARDS:

NAME & INITIALS: AGE:

QUALIFICATIONS (eg. degree/diploma, issuing institution and date):

SPECIAL AWARDS:

NAME & INITIALS: AGE:

QUALIFICATIONS (eg. degree/diploma, issuing institution and date):

SPECIAL AWARDS:

Use a continuation sheet if necessary

5.2 Revelant Experience and Publications (one page for each individual listed in 5.1)

NAME: T R STACEY

Relevant Experience:

1. More than 20 years of experience in rock mechanics.
2. Significant involvement on a project to overcome the rockburst problem in a large mine. Involved in the preparation of blasting tests of rockburst support, and observation of the results of the tests.

Relevant Publications:

Stacey, T R (1992) Stability of underground mine openings at great depth, Proc. Int. Conf. Geomechanics 91, Ostrava, Czechoslovakia, ed Z Rakowski, A A Balkema, Rotterdam, pp 17-25.

Ortlepp, W D and Stacey, T R (1992) Rockburst mechanisms in tunnels and shafts, Proc. TUNCON '92, Maseru, Lesotho, September 1992

Kirsten, H A D and Stacey, T R (1988) Destabilising effects of seismic disturbances on fractured rock surrounding tabular stopes, Proc. 2nd Int. Symp. on Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Kirsten, H A D and Stacey, T R (1988) Hangingwall behaviour in tabular stopes subjected to seismic events, Jl S. Afr. Inst. Min. Metall., v88, no 5, May 1988, pp 163-172.

TRS

5.2 Revelant Experience and Publications (one page for each individual listed in 5.1)

NAME: W D ORTLEPP

Relevant Experience:

1. More tahn 30 years of experience in rock mechanics.
2. Has designed and supervised three sets of blasting tests on support in the past.
3. Extensive experience with rockburst conditions and support.
4. International consultant on rockbursts and support.

Relevant Publications:

1. Performance of a Yielding Rock-stud Under Impulse Loading Conditions. Symp. on Large Permanent Underground Openings, Oslo 1969.
2. Consideration in the Design of Support for Deep Hard-Rock Tunnels. 5th Int. Congress of ISRM, Melbourne, 1982.
3. Impulse-load Testing of Tunnel Support. Int. Symp. on Rock Support, Laurentian University, June 1992.
4. The design of Support for the Containment of Rockburst Damage in Tunnels - an Engineering Approach. Int. Symp. On Rock Support, Laurentian University, June 1992.
5. Grouted rock-studs as rockburst support
   - a simple design approach and an effective test procedure Journ. SAIMM, February 1994.

RS

6. DECLARATION BY THE PROPOSING ORGANIZATION

I, the undersigned, being duly authorized to sign this proposal, herewith declare that:

- The information given in this proposal is true and correct in every particular.
- This Organization has the basic expertise and facilities required for satisfactory completion of the project and will adhere to the program of activities as set out in this proposal.
- The costs quoted are in accordance with the normal practice of this Organization and can be substantiated by audit.

Signed on this 29 day of July 1994 for and behalf of

Steffen, Robertson and Kirsten

SIGNATURE:

NAME: T R Stacey

DESIGNATION: Director

TRS

APPENDIX B

TABULATED TEST RESULTS

(DAVE3.WB2)

TABLE B1

100 x 3,5mm Square Weld Mesh (Series 1.2)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
1	200	1.98	650	1.28	31	Wires broken	0	0	0	0	
	303	2.44	650	1.93	35		2 @ bolt	0	0	0	First drop
						Bricks broken	0				Second drop
2	605	3.45	650	3.86	101	Wires broken	2	2	0	1 wire 2 welds	
						Bricks broken	0				
3	605	3.45	650	3.86	85	Wires broken	2 @ corner	0	0	0	
	500	3.13	650	3.19	113		2 + 0	1	0	0	First drop
						Bricks broken	0				Second drop
15	1000	4.43	650	6.38	98	Wires broken	0	2	1	1	Wires broken at washer plates
						Bricks broken	3				
17	1400	5.24	650	8.93	106	Wires broken	1	2	2	1	Wires broken at washer plates
						Bricks broken	7 whole bricks				

TABLE B2

100 x 4,0mm Square Weld Mesh (Series 1.3)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
8	1400	5.24	650	8.93	107	Wires broken	0	2	1	2	
						Bricks broken	1 split brick + 7 whole bricks				
9	1400	5.24	650	8.93	110	Wires broken	0	2	2	2	Demo to Brunswick Mining
						Bricks broken	0 split bricks + 8 whole bricks				
10	1200	4.85	650	7.65	99	Wires broken	1	1	1	0	Curvature very small (est. 1,6%, say 20mm)
						Bricks broken	4				
22	1100	4.65	650	7.01	141	Wires broken	1 behind plate, 2 @ welds	2 @ plate, 1 @ weld	1 behind plate	0	No bricks spilled
						Bricks broken	2 Split bricks + 5 whole bricks				

TABLE B3

100 x 3,2mm Diamond Mesh (Series 2.1)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION NW	SW	SE	NE	
4	1000	4.43	650	6.38	144	Wires broken	0	0	0	0	6mm and 9mm gap below plate
						Bricks broken	6				
5	1400	5.24	650	8.93	148	Wires broken	0	0 cons. strech	0	0	14mm gap below plate
						Bricks broken	6				
‘6	1700	5.78	650	10.84	116	Wires broken	0	0	0	0	11mm gap below plate
						Bricks broken	3 split bricks + 1 whole brick				
7	1900	6.11	650	12.12	246	Wires broken	1 gap @ corner	0	0	0	1 broken wire allowed unravelling,
						Bricks broken	9				5 bricks spilled through gap

TABLE B4

75 x 3,2mm Diamond Mesh (Series 2.2)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
11	1500	5.42	650	9.56	178	Wires broken	1 @ link	0	0	0	no photos
						Bricks broken	7				
12	1700	5.78	650	10.84	167	Wires broken	1 @ interlink	0	0	0	No bricks spilled
						Bricks broken	6 whole bricks				
13	1900	6.11	650	12.12	202	Wires broken	0	2	0	0	Unravelled @ SW 1 brick spilled out
						Bricks broken	10				
14	2100	6.42	650	13.39	201	Wires broken	1	0	0	1	Minor unravelling No bricks spilled
						Bricks broken	9				
16	2500	7.00	650	15.94	273	Wires broken	1	1	0	0	Unravelled @ NW & SW 2 bricks spilled out
						Bricks broken	1 split brick + 12 whole bricks				

TABLE B5

100 x 4,0mm Diamond Mesh (Series 2.3)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
18	1700	5.78	650	10.84	208					1	Unravelling @ NE
						Bricks broken	1 split brick + 10 whole bricks				One block spilled out
19	1900	6.11	650	12.12	192	Wires broken	0	0	0	0	
						Bricks broken	8 whole bricks				
20	2100	6.42	650	13.39	224	Wires broken	0	0	0	0	
						Bricks broken	11 whole bricks				
21	2500	7.00	650	15.94	209	Wires broken	0	0	0	0	
						Bricks broken	2 split bricks + 13 whole bricks				

TABLE B6

75 x 3,2mm Diamond Mesh With De-strand Lacing (Series 3.1)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
34	1750	5.86	2706	46.46	destroyed	Wires broken	2 @ interlink	4 @ interlink	2 @ interlink	3 @ interlink	GAPREAG demo
						Lacing	NE-SW slipped completely, NW-SE slipped 290 to 450mm				H.S. video by In-Depth Videos Ltd
						Bricks broken	3 split bricks + 22 whole bricks				Slippage of lacing led to collapse
35	1250	4.95	2706	33.18	243	Wires broken	0	2	1	2	SRK video by Bruce
						Lacing	no damage, slippage 100 mm NW, 130 mm SW				No bricks spilled
						Bricks broken	4 split bricks + 15 whole bricks				

TABLE B7

100 x 3,2mm Diamond Mesh With De-strand Lacing (Series 3.2)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
33	1750	5.86	2706	46.46	destroyed	Wires broken	2 @ interlink	2 @ interlink	3 @ interlink	3 @ interlink	Diagonal lacing slipped at staywires
						Lacing	no damage, 230 mm slip NE, 140 mm slip NW				but not freed
						Bricks broken	7 split bricks + 16 whole bricks				
36	1250	4.95	2706	33.18	295	Wires broken	1	1	1	1	SRK video slight unravelling
						Lacing	no damage, slippage 165 mm SW, nil NW				No bricks spilled
						Bricks broken	4 split bricks + 15 whole bricks				
37	3300	8.05	1048	33.93	273	Wires broken	1	0	1	2	Unravelling @ NE and NW. 2 blocks
						Lacing	no damage, slippage 180 mm NW, 100 mm SW				fell through, Chain link connectors
						Bricks broken	2 split bricks + 17 whole bricks				Photo 9
55	2660	7,3	2706	70,6	397	Wires broken	2	2	1	2	Mesh unravelled in all 4 quadrants
						Lacing	no damage				7 bricks fell through
						Bricks broken	1 split brick + 33 whole bricks				

TABLE B8

100 x 3,2mm Diamond Mesh With 8mm Lacing (Series 3.3)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
23	2200	6.57	1048	22.62	160	Wires broken	0	0	0	0	First use of 1048kg mass. Lacing taut, > 10kN. Marked expulsion of dust
						Lacing	no damage				
						Bricks broken	1 split brick + 18 whole bricks				
24	2800	7.41	1048	28.79	413	Wires broken	1 @ plate	1 @ plate	2 @ plate	0	Lacing taut, > 10 kN. Severe unravelling at NW and SE 6 bricks spilled
						Lacing broken	SW at plate, NW at plate				
						Bricks broken	3 split bricks + 17 whole bricks				
25	2800	7.41	1048	28.79	353	Wires broken	1	1	1	0	Lacing taut, >10kN, unravelling @ NW and SW corners 2 bricks spilled
						Lacing broken	NW at plate, SE at centre				
						Bricks broken	3 split bricks + 19 whole bricks				
26	2500	7.00	1048	25.70	353	Wires broken	1 @ plate	2 @ interlink	1 @ interlink	0	Very taut, approx. 12kN, unravelling @ NW and SW corners 4 bricks spilled
						Lacing broken	NW at plate, SW at plate				
						Bricks broken	2 split bricks + 18 whole bricks				
30	2800	7.41	1048	28.79	221	Wires broken	1 @ interlink	0	0	1 @ interlink	1 lacing rope slid @ crosby clamp (tightened as usual). No brick spilled (Slack-laced, square plates)
						Lacing	NW broken, NE 1 strand broken				
						Bricks broken	4 split bricks + 17 whole bricks				

TABLE B8 (Continued)

100 x 3,2mm Diamond Mesh With 8mm Lacing (Series 3.3)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
31	3200	7.92	1048	32.90	176	Wires broken	0	0	1 @ interlink	0	Slightly slack 8 mm lacing, earred plates
						Lacing	no damage				
						Bricks broken	3 split bricks + 25 whole bricks				
43	3630	8.44	1048	37.32	Destroyed	Wires broken	?	?	?	?	Destroyed - Impact photo 14
						Lacing	Lacing failed at yielding knot				8mm Zig-zag lacing.
						Bricks broken	25 whole bricks				Single clamp yielding - low torque
44	3000	7.67	1048	30.84	232	Wires broken	2	0	1		8mm Zig-zag lacing- low torque
						Lacing	No damage				200 mm yielding on NW loop
						Bricks broken	1 split brick 18 whole bricks				3 bricks spilled out
45	3630	8.44	1048	37.32	Destroyed	Wires broken	?	?	?	?	Destroyed - Impact photo 15
						Lacing	Lacing failed, N leg @ centre				8mm Zig-zag lacing
						Bricks broken	23 whole bricks				Double clamp - 20 Nm torque
53	3630	8.44	1048	37.32	377	Wires broken	1	1	0	1	8mm Zig-zag lacing
						Lacing	North yielded 390mm, South yielded 135mm				Two double - clamp yield loops (15N
						Bricks broken	3 split bricks + 27 whole bricks				2 bricks spilled through

TABLE B9

100 x 3,5mm Weld Mesh With 10mm and 12mm Lacing (Series 4.1)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION NW	SW	SE	NE	
32	1750	5.86	2706	46.46	309	Wires broken	4	4	4	5	Crosby clamp tight as possible tension close to 10 kN. De-strand 12mm lacing taut. No bricks spilled
						Lacing	no damage. Slipped free from NE washer plate				
						Bricks broken	5 split bricks + 27 whole bricks				
38	3300	8.05	1048	33.93	205	Wires broken	1	3	2	3	No brick fell through Semi-taut 10 mm lacing, chain link connectors
						Lacing	no damage. No slippage				
						Bricks broken	3 split bricks + 23 whole bricks				
39	3630	8.44	1048	37.32	211	Wires broken	2	3	2	1	Max. velocity possible 8,5m/s No bricks fell through, Semi-taut 10 mm lacing, chain link connectors
						Lacing	no damage. No slippage				
						Bricks broken	3 split bricks + 24 whole bricks				
56	2660	7,3	2706	70,6	448	Wires broken	7	7	5	5	12mm de-strand lacing, did not slip Many bricks spilled out
						Lacing	no damage				
						Bricks broken	3 split bricks + 35 whole bricks				

TABLE B10

100 x 3,5mm Weld Mesh With 8mm Lacing (Series 4.2)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
27	1800	5.94	1048	18.51	146	Wires broken	2@ pl, 3@ weld	1 @ plate	1 @ weld	0	Lacing very taut +-12kN
						Lacing broken	3 of 6 strands, 4 of 6 strands @ sharp edge of washers				no bricks spilled
						Bricks broken	3 split bricks + 14 whole bricks				
28	1800	5.94	1048	18.51	139	Wires broken	5 @ weld	2 @ weld	0	0	Lacing very taut +-12 kN
						Lacing broken	NW slight damage, SW 4 of 6 strands broken				before drop, rigid after
						Bricks broken	2 split bricks + 19 whole bricks				No bricks spilled
29	2200	6.57	1048	22.62	158	Wires broken	3 @ plate	1	3 @ plate	2 @ weld	Earred plates. Lacing slack-
						Lacing	no damage				(0,2kN before drop, 1,7 kN after)
						Bricks broken	3 split bricks + 14 whole bricks				
46	3630	8.44	1048	37.32	266	Wires broken	3	3	2	2	Double clamp 15 Nm torque
						Lacing	no damage. 310 mm yield at SW				8mm lacing zig-zag
						Bricks broken	2 split bricks + 29 whole bricks				No bricks spilled
54	1900	6.00	2706	50,5	443	Wires broken	5	4	6	5	All failed wires were around
						Lacing	Diagonals slipped by 346 mm and 300 mm				connectors. Additionally 2 broke
						Bricks broken	3 split bricks + 26 whole bricks				at centre. 1 split brick spilled

TABLE B11

Shotcrete Reinforced With 100 x 4mm Weld Mesh (Series 5.1)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
40	1500	5.42	1048	15.42	215	2 major cracks (NS, EW), all wires crossing these cracks were broken, only fringe unbroken Broken bricks: 14					First shotcrete slab to be tested All mesh strands crossing 2 main cracks are broken photo 23

TABLE B12

100mm Shotcrete - 50mm Monofil. Polypro. (Series 6.1)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION NW	POSITION SW	POSITION SE	POSITION NE	
	1000	4.43	1048	10.28	74						No photograph or sketch
47	1000	4.43	1048	10.28	Destroyed	Broken bricks : 19					Destroyed at 2nd drop
	1500	5.42	1048	15.42	162	Crack width : 75mm					Crack configuration shown in Fig 21
49	750	3.84	1048	7.71	323	Crack width : 200mm					Photo 26
						Broken bricks: 14					
	1250	4.95	1048	12.85	97	Crack width : 25mm					Crack configuration shown in Fig 21
50	450	2.97	1048	4.63	Destroyed	Broken bricks: 14					and photo 25. Destroyed at 2nd drop.
											1 brick spilled out
	1000	4.43	1048	10.28	72	Crack width : 20mm					Pre-existing flaw right across corners
52	500	3.13	1048	5.14	Destroyed	Broken bricks: 13					of slab. Depth = 1/2 slab thickness.
											Crack configuration shown in Fig 22
											and photo 24

TABLE B13

Shotcrete - No Reinforcing (Series 7.1)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
	250	2.21	1048	2.57	2						Cracks all formed after first drop
41	150	1.72	1048	1.54	13	Bricks broken: 2					Fig 19 shows crack pattern
	250	2.21	1048	2.57	38						2nd drop widened cracks

TABLE B14

Shotcrete Reinforced With 30mm Dramix (2,75% By Mass) (Series 8.1)

TEST No.	DROP HEIGHT (mm)	VEL. (m/s)	MASS (kg)	KIN. ENERGY (kJ)	CUM. POST DROP DEFL. (mm)	DAMAGE DESCRIPTION					REMARKS
						SUPPORT ELEMENT	POSITION				
							NW	SW	SE	NE	
42	1000	4.43	1048	10.28	30						Many cracks formed, see Fig 20 for crack pattern
	1000	4.43	1048	10.28	118	Bricks broken: 22					
	1000	4.43	1048	10.28	378						
48	1500	5.42	1048	15.42	60	Crack width : 6mm					For crack configuration see Fig 20
	1000	4.43	1048	10.28	223	Crack width : 75mm					
	500	3.13	1048	5.14	Destroyed	Bricks broken: 18					
51	2000	6.26	1048	20.56	102	Crack width : 30mm					For crack configuration see Fig 22
	1000	4.43	1048	10.28	Destroyed	Bricks broken: 25					Destroyed (effectively)

APPENDIX C

REPRESENTATIVE PHOTOGRAPHS OF THE TEST FACILITY AND OF THE TESTS

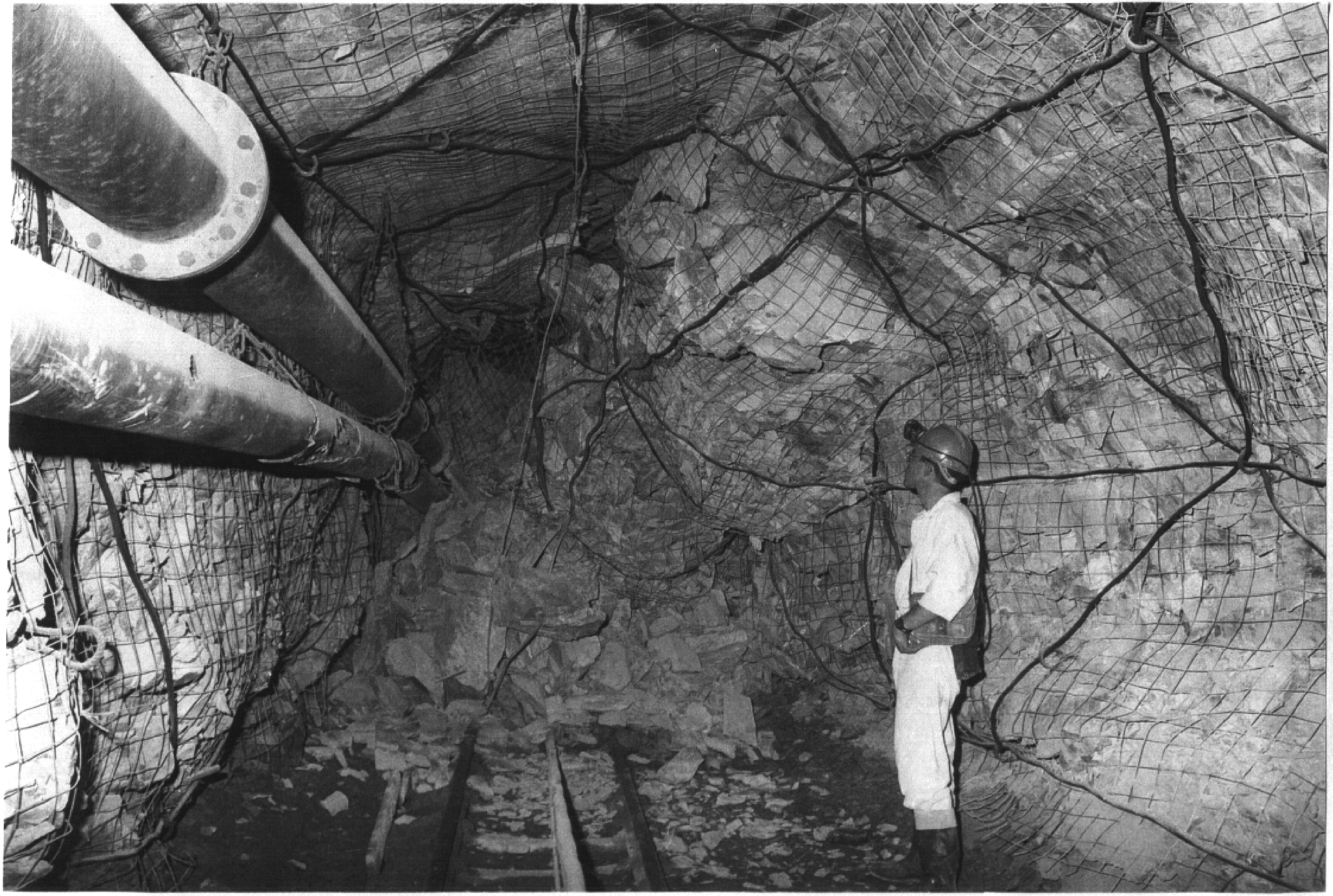


Photo 1: View along tunnel in footwall quartzite at 2500 m depth showing varying intensity of damage to support ranging from slight bulging to complete destruction.

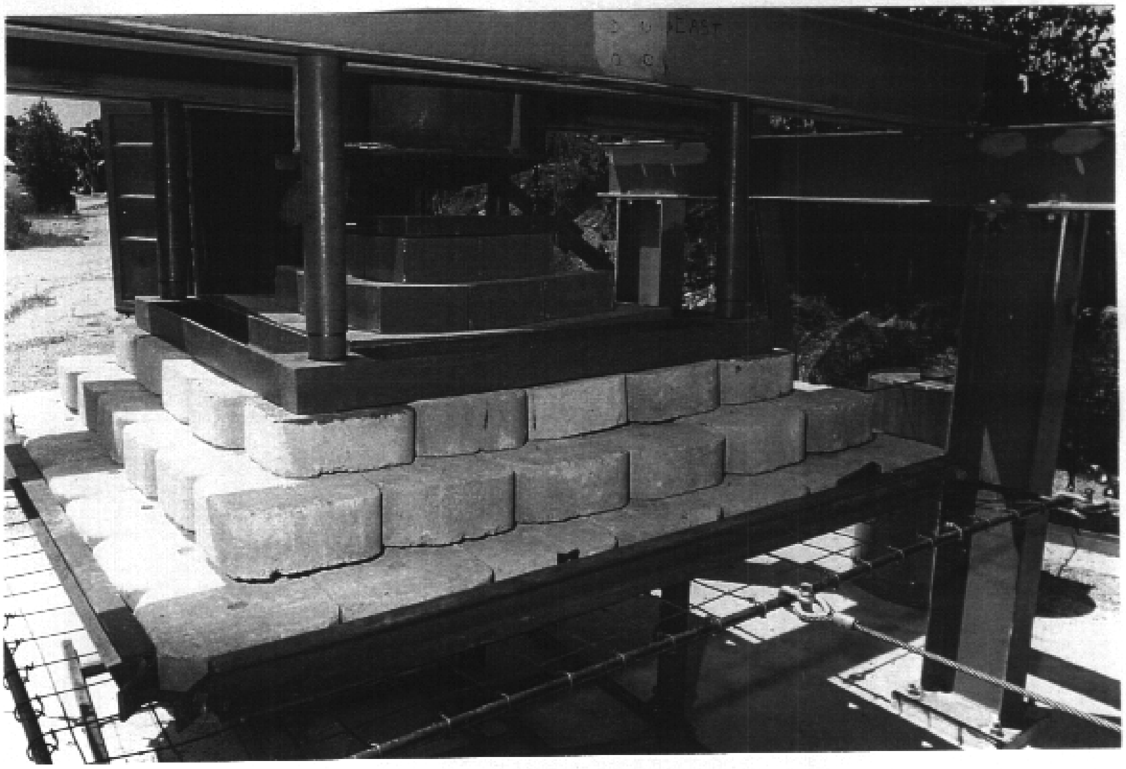


Photo 2: View of test arrangement showing three layers of load distribution blocks beneath the impact plate and three layers of concrete blocks simulating the fractured rock above the mesh sample.

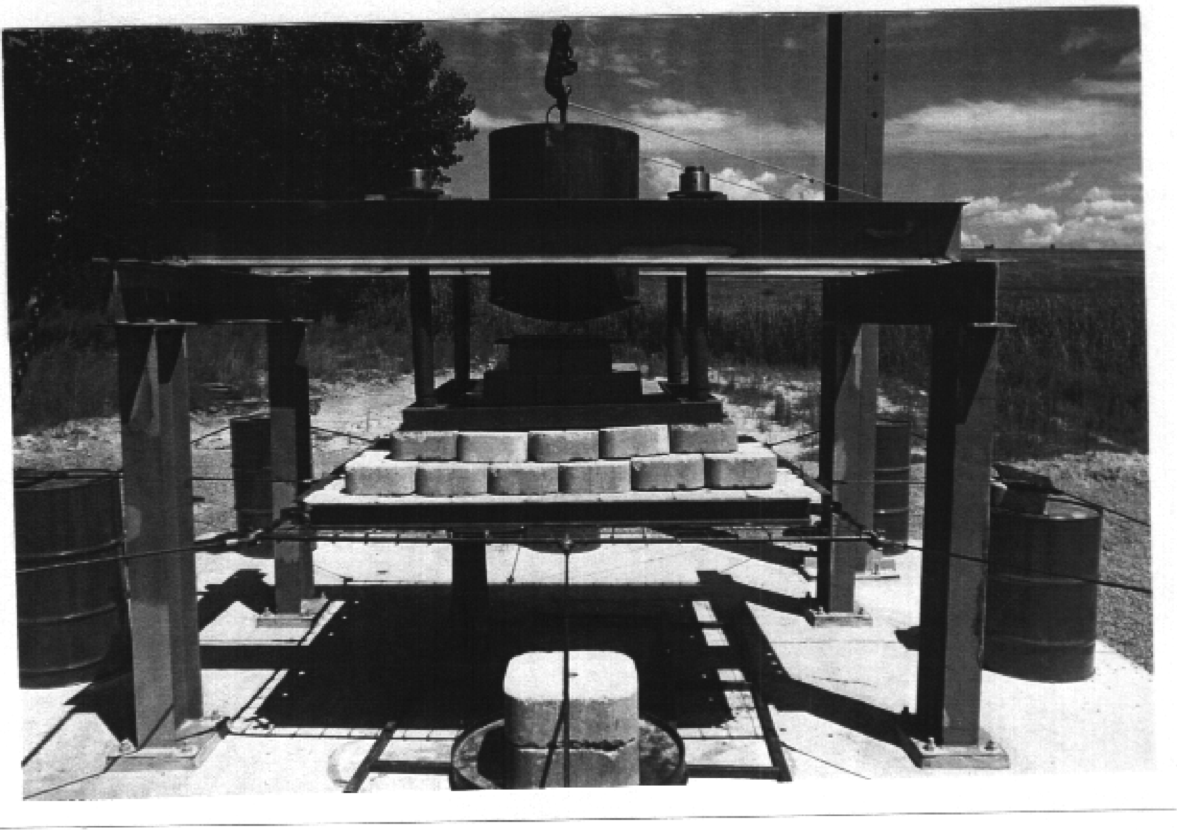
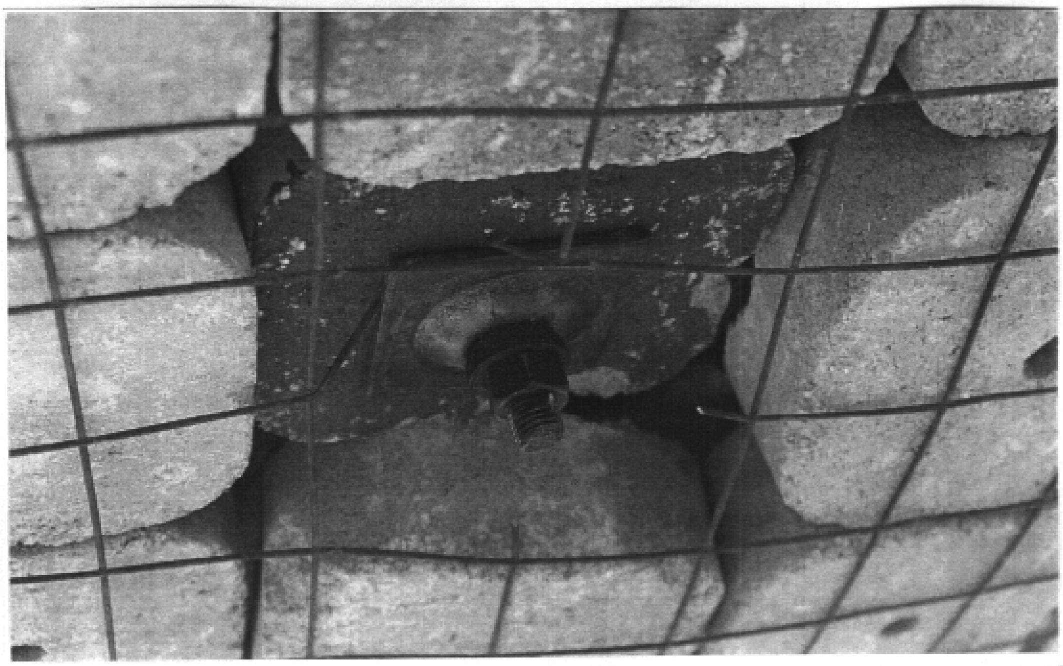
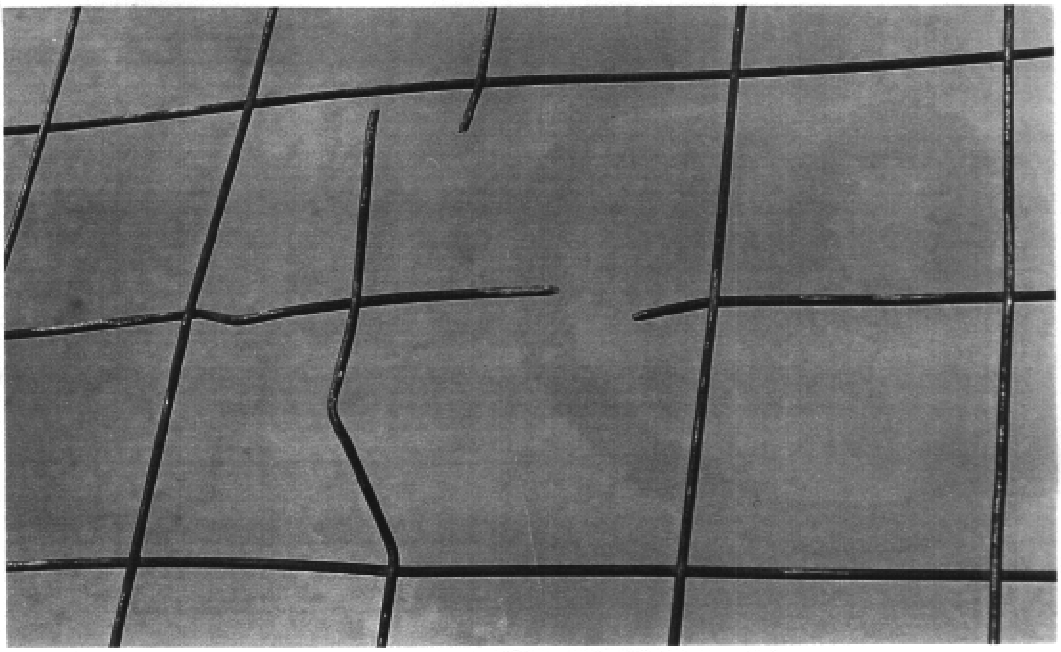


Photo 3: General view of test arrangement suspended from steel superstructure.

Photo 4: View of suspension of drop weight from overhead trolley.



a) Detail of weldmesh strands guillotined by sharp edges of square domed faceplate



b) Close view of sheared wire strands

Photo 5: **Test No. 2. Impulse of 3,9 kJ caused 101 mm of centre deflection.**

Photo 6: **Test No. 7. Impulse 12,1 kJ, 246 mm deflection.**
View of underneath of diamond mesh test specimen showing unravelling at N-W corner and five blocks spilled.

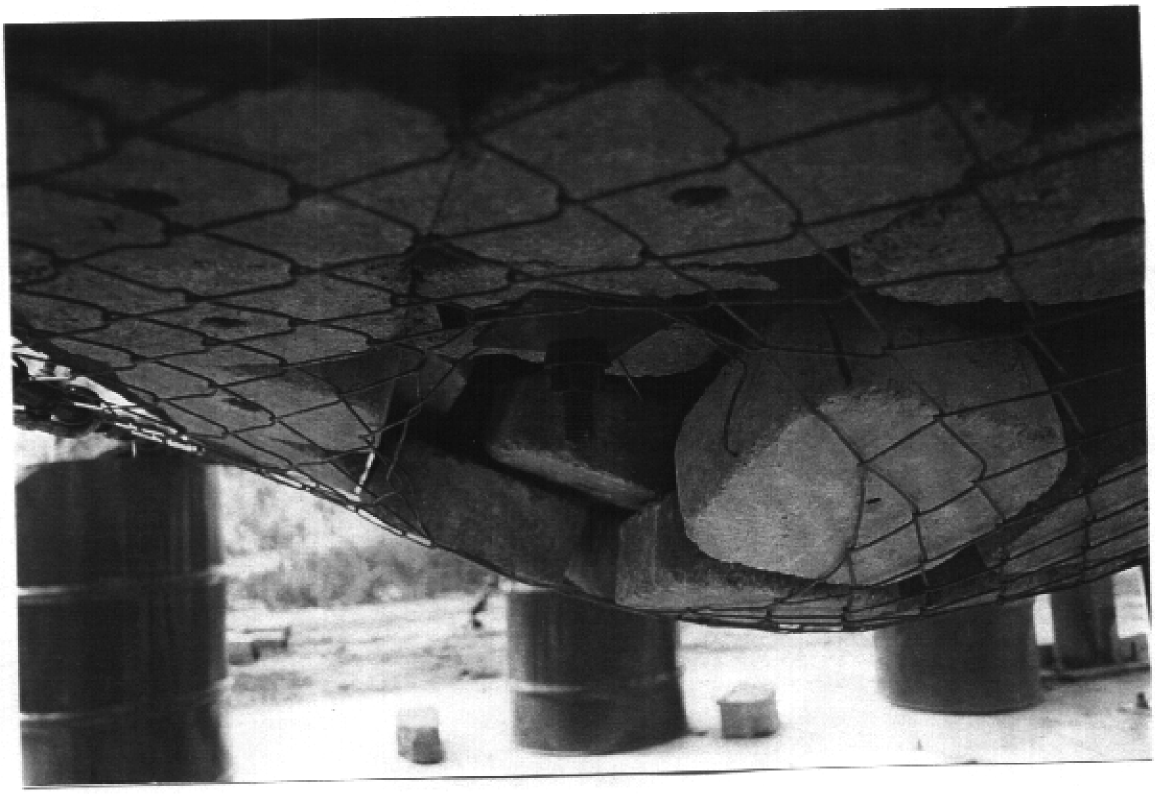


Photo 7: **Test No. 16. Impulse 15,9 kJ, 273 mm centre deflection.**
Two wires of 75 mm aperture diamond mesh broke leading to unravelling and spilling out of bricks.

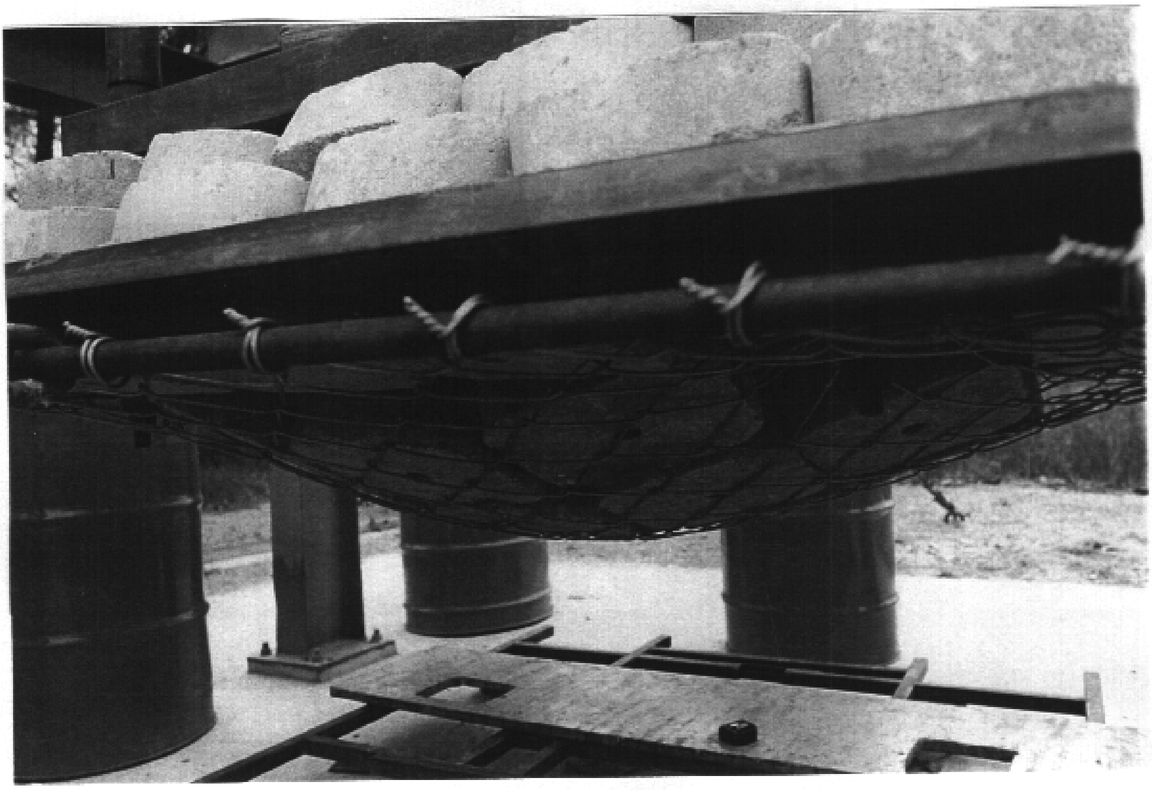


Photo 8: **Test No. 21. Impulse 16 kJ, 209 mm centre deflection.**

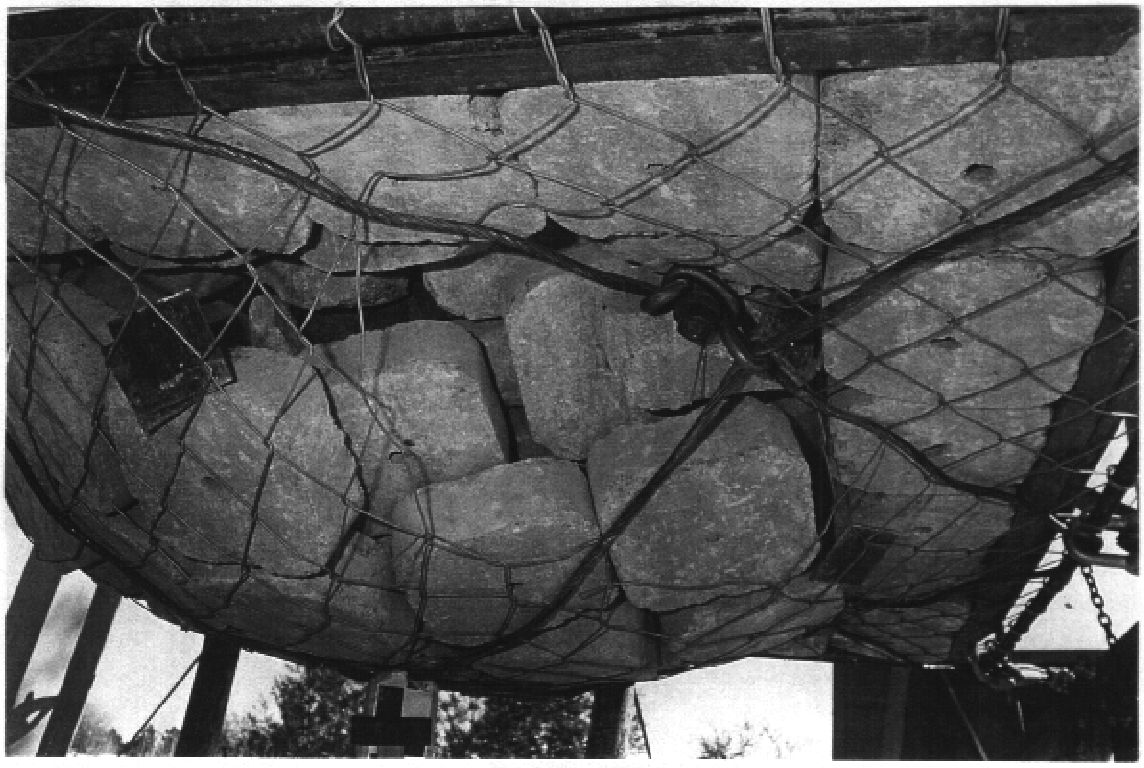
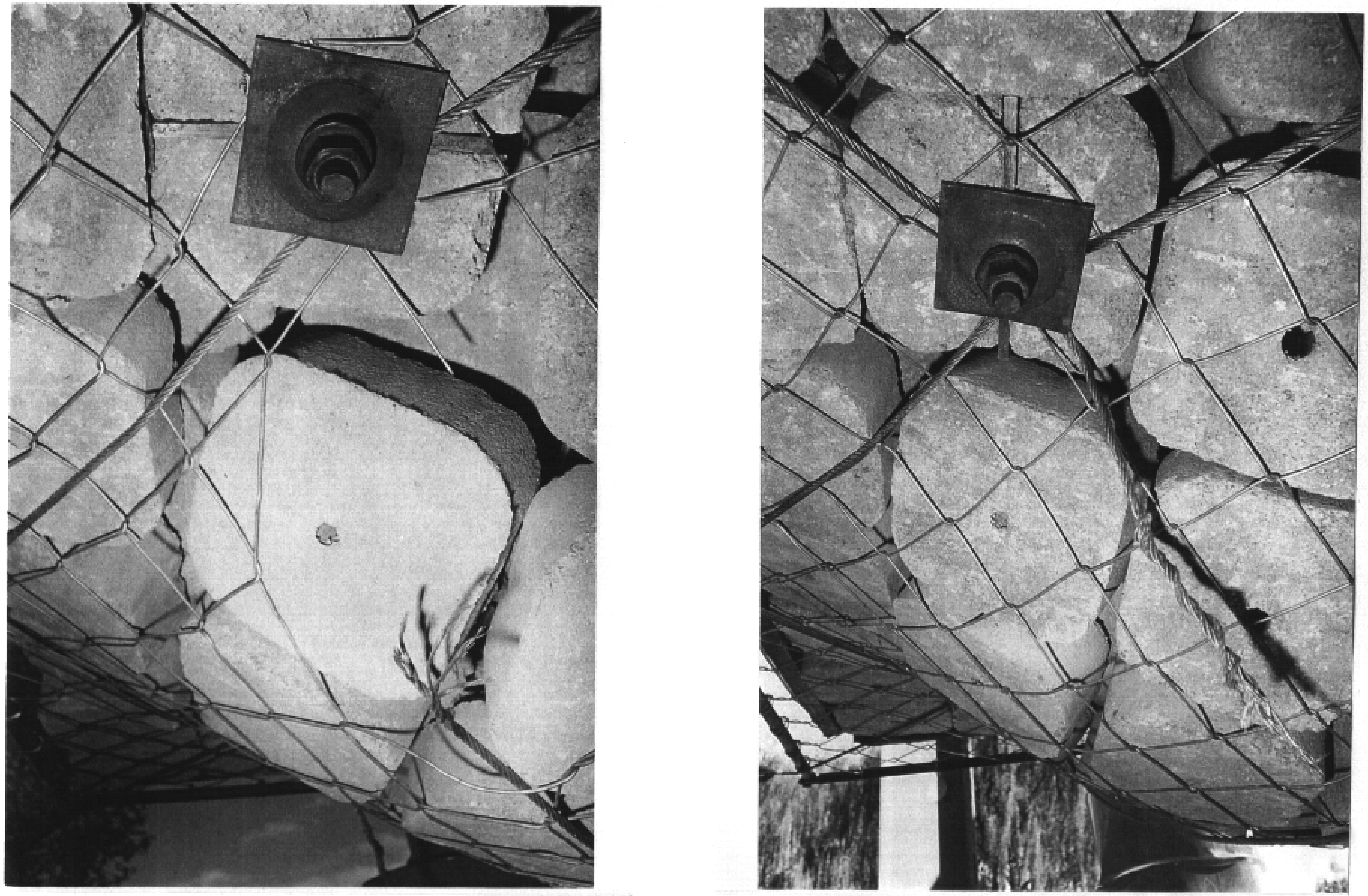


Photo 9: **Test No. 37. Impulse 33,9 kJ, 273 mm deflection.**
Two wires broke at interlock leading to unravelling and spilling of one brick.

Photo 10: **Test No. 55. Impulse 70,6 kJ, 397 mm deflection.**
Mesh unravelled in all four quadrants leading to spilling of seven bricks.

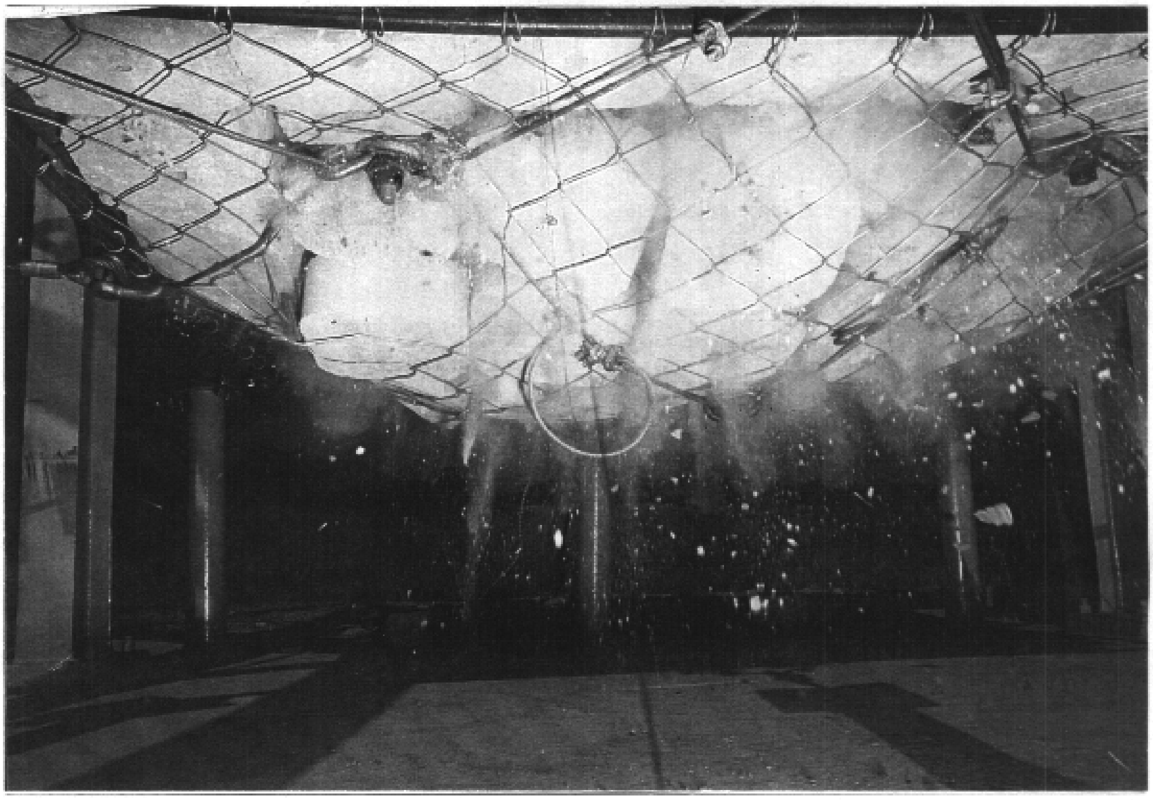


a) The 8 mm lacing failed at the N-W face plate on one diagonal.

b) The other diagonal of lacing failed at the centre.

Photo 11: **Test No. 25. Impulse 29kJ, 353 mm of deflection.**

Photo 12: **Test No. 43. Impulse of 37,3 kJ caused complete collapse.**
Detail of northern loop before impact. One Crosby clamp at low torque.



a) Approximately 100 m/s after impact. First wire has broken and unravelling has commenced.

b) 200 mm of yield on northern main strand of zig-zag lacing has prevented failure of lacing but bricks have spilled out.

Photo 13: **Test No. 44. Impulse of 31kJ, 232 mm deflection.**

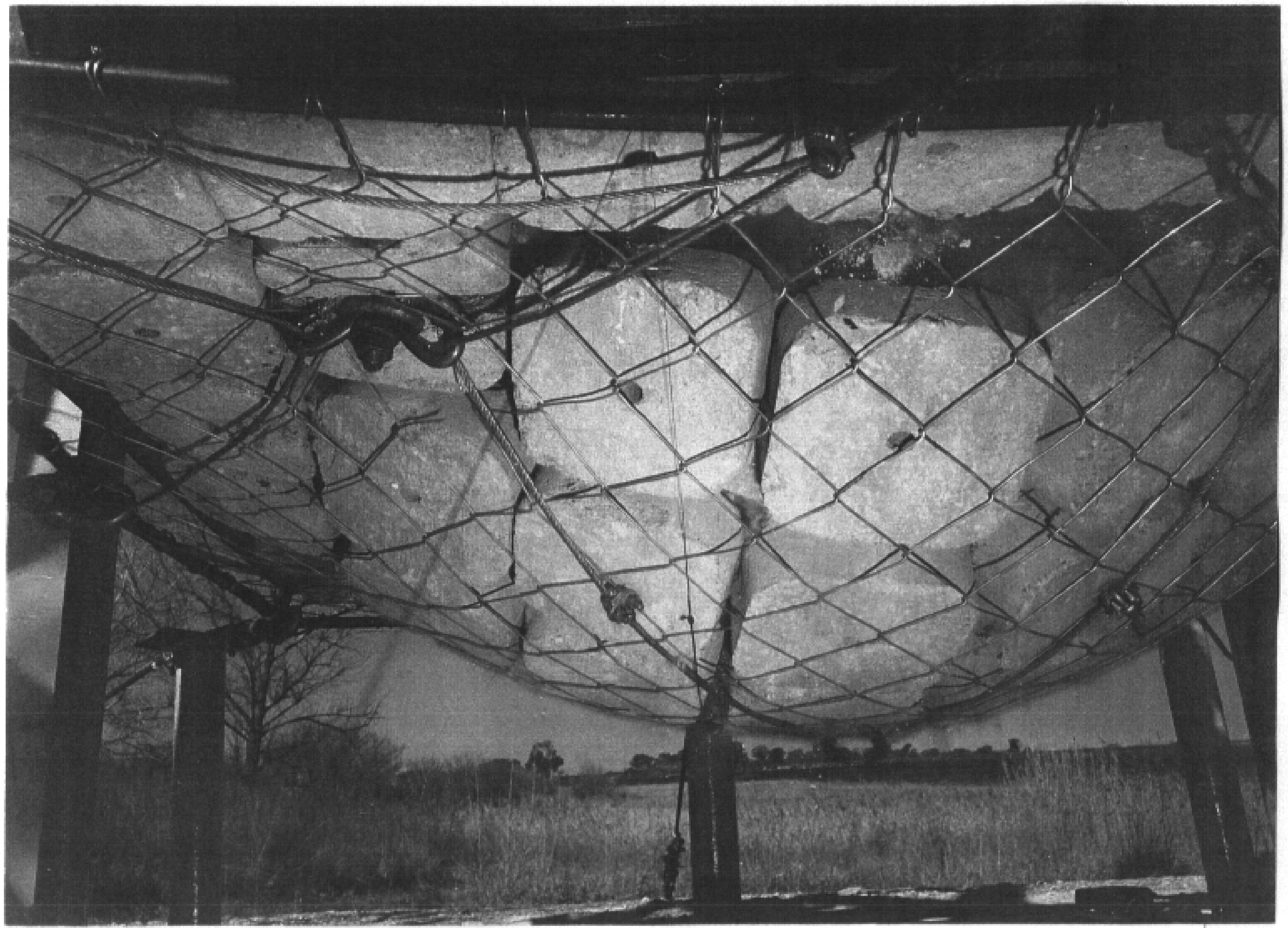


Photo 14: **Test No. 43. Impulse of 37 kJ at impact velocity of 8,4 m/s.**
Microseconds before failure of 8 mm lacing occurred at southern yielding loop. Loop failed because of easy slip of single Crosby clamp tightened to low torque of less than 10 Nm. First wire of diamond mesh has failed near N-W chain link connector at interlock. The panel was totally destroyed a fraction of a second later!

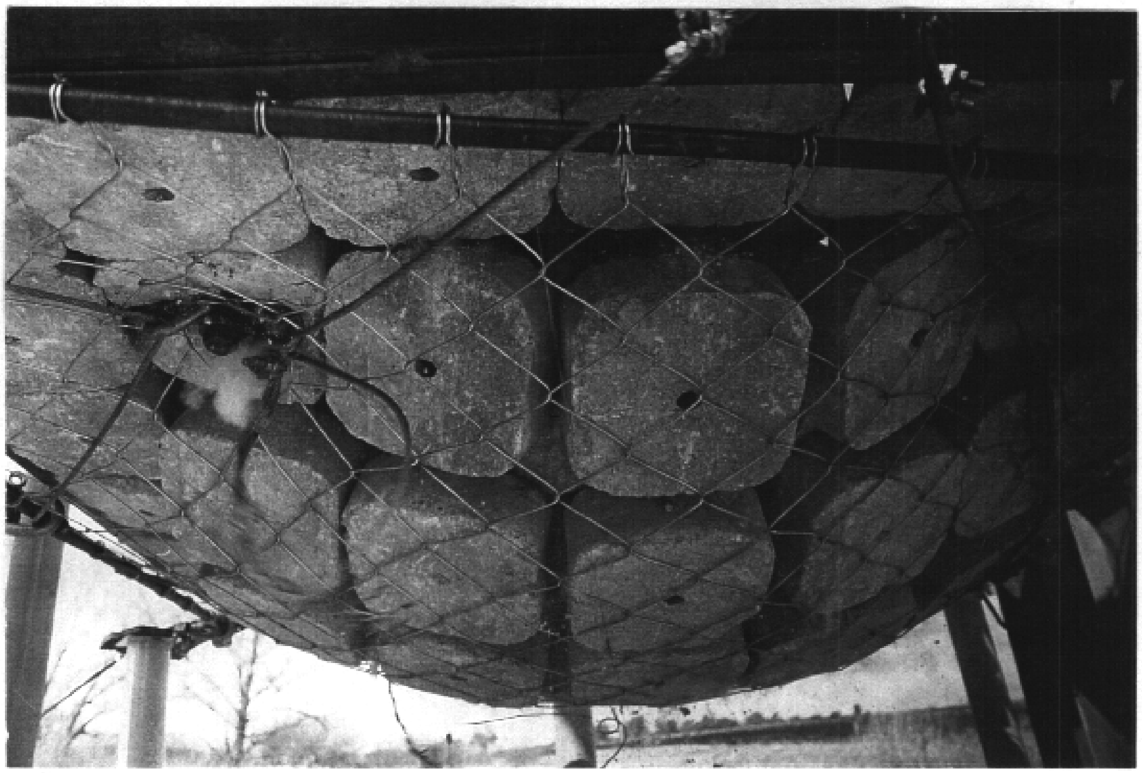
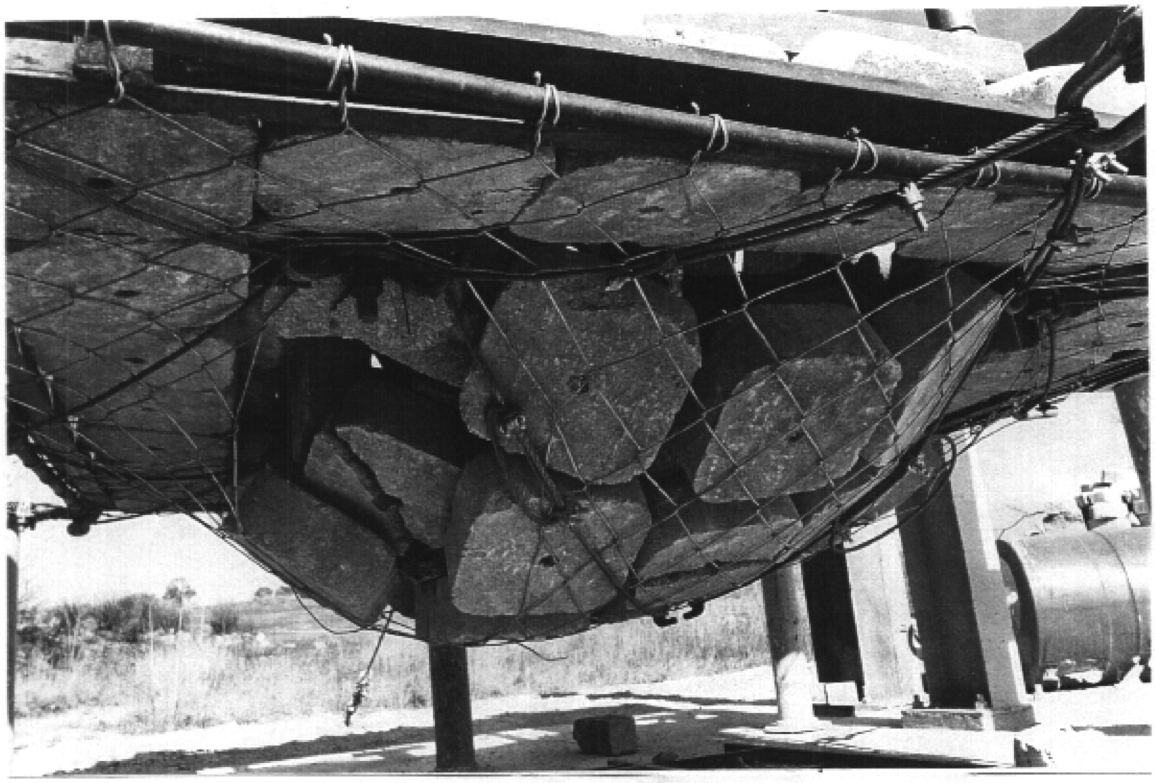


Photo 15: **Test No. 45. Impulse was 37 kJ at impact velocity of 8,4 m/s.**
View taken about 0,25 seconds after impact. Broken end of rope is flailing about. West-most yielding clamp has been pulled into N-W chain link. Right angle bend prevents further yield and is thus the probable cause of failure.



a) N-W corner; approx. 540 mm of yield occurred along centre strand of the zigzag lacing.

b) S-W corner; approx. 380 mm of yield occurred at loop clamped with 2 Crosby clamps tightened to 15 Nm.

Photo 16: **Test No. 53. Impulse 37 kJ, deflection 377 mm.**
Substantial damage was caused to mesh.

Photo 17: **Test No. 31. Impulse 32,9 kJ, 176 mm deflection.**
Use of 'eared' lacing-plates has prevented damage to 8 mm lacing. Unravelling of diamond mesh has commenced but no brick spilled.

Photo 18: **Test No. 39. Impulse 37 kJ, deflection 211 mm.**
100 x 3,5 weld mesh was backed by 10 mm lacing connected to rock bolts by 3-link chain-link connectors.

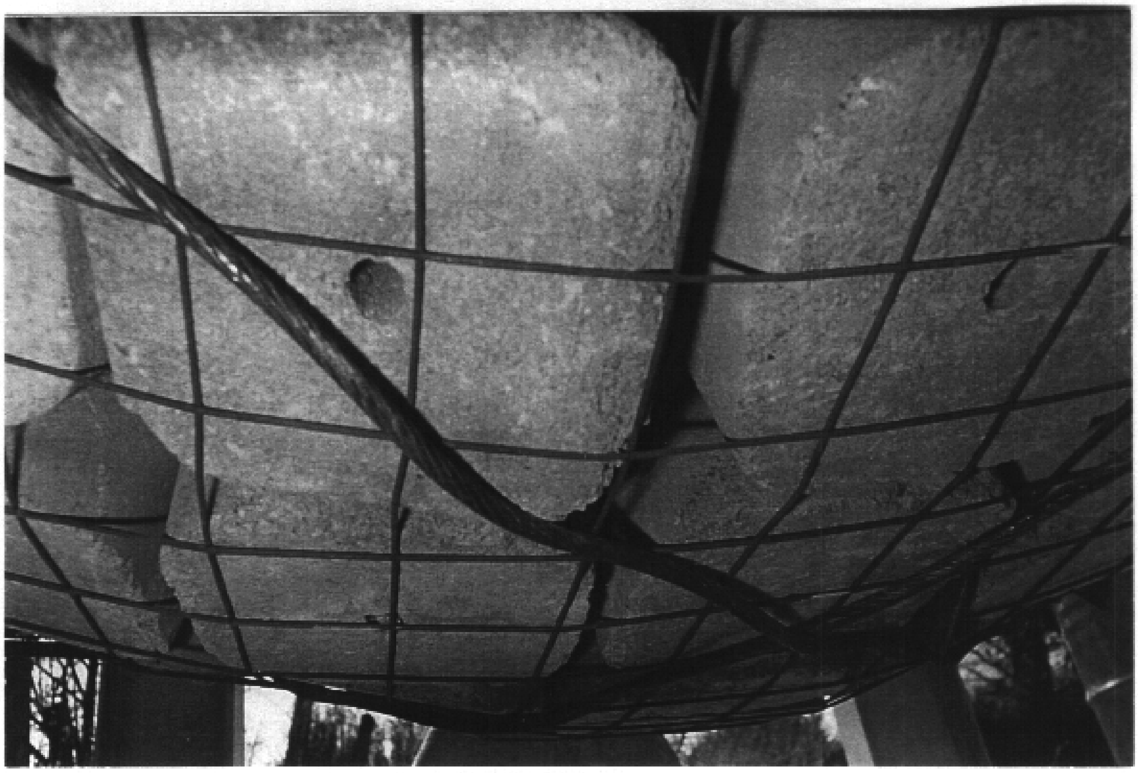


Photo 19: **Test No. 32. Impulse 46,5 kJ, 309 mm deflection.**
Cross-over of 12 mm destranded lacing at centre. No damage to wires or lacing.

Photo 20: **Test No. 56. 70,6 kJ at impact velocity of 7,3 m/s.** Photo taken about 0,3 seconds after impact.

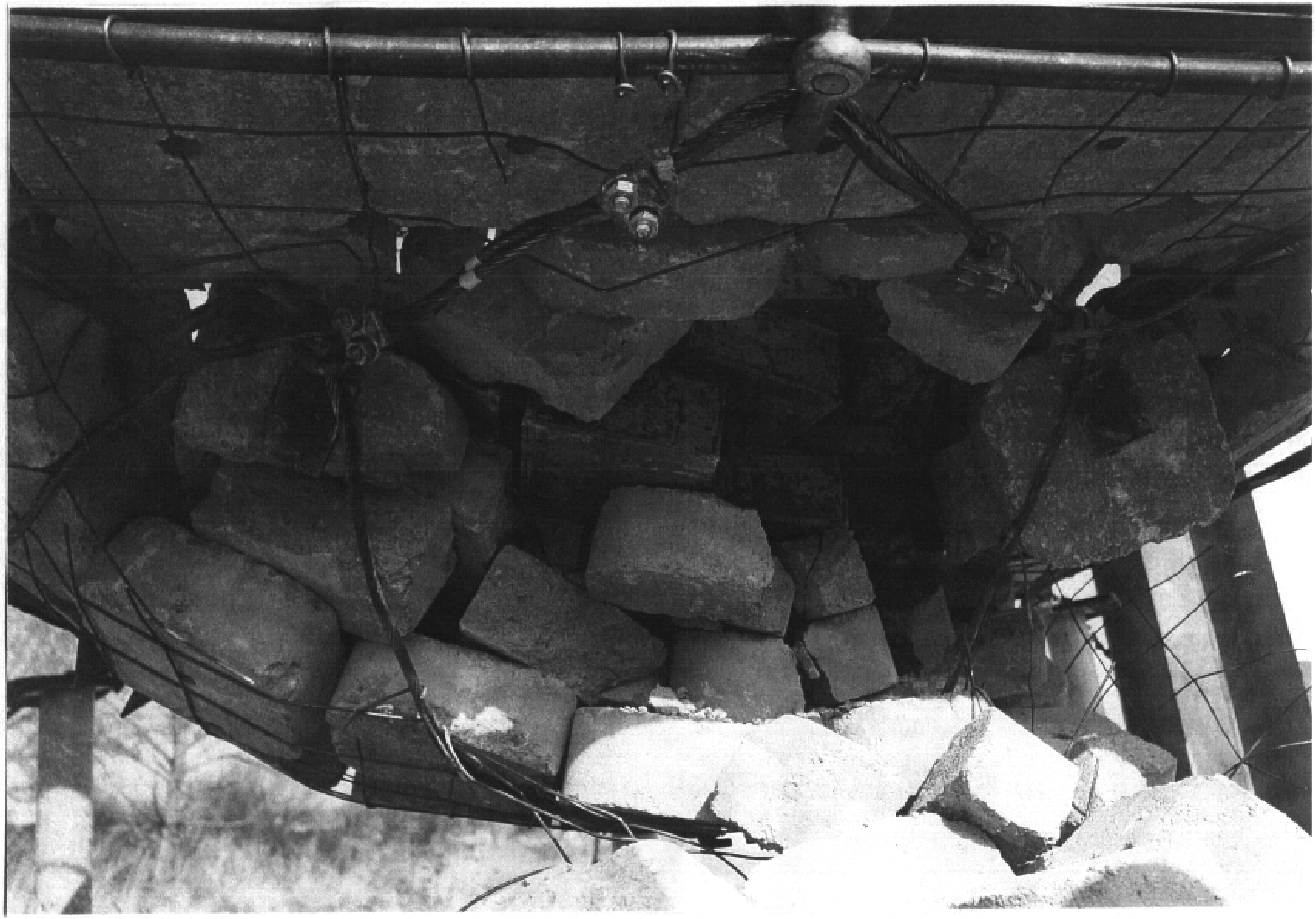
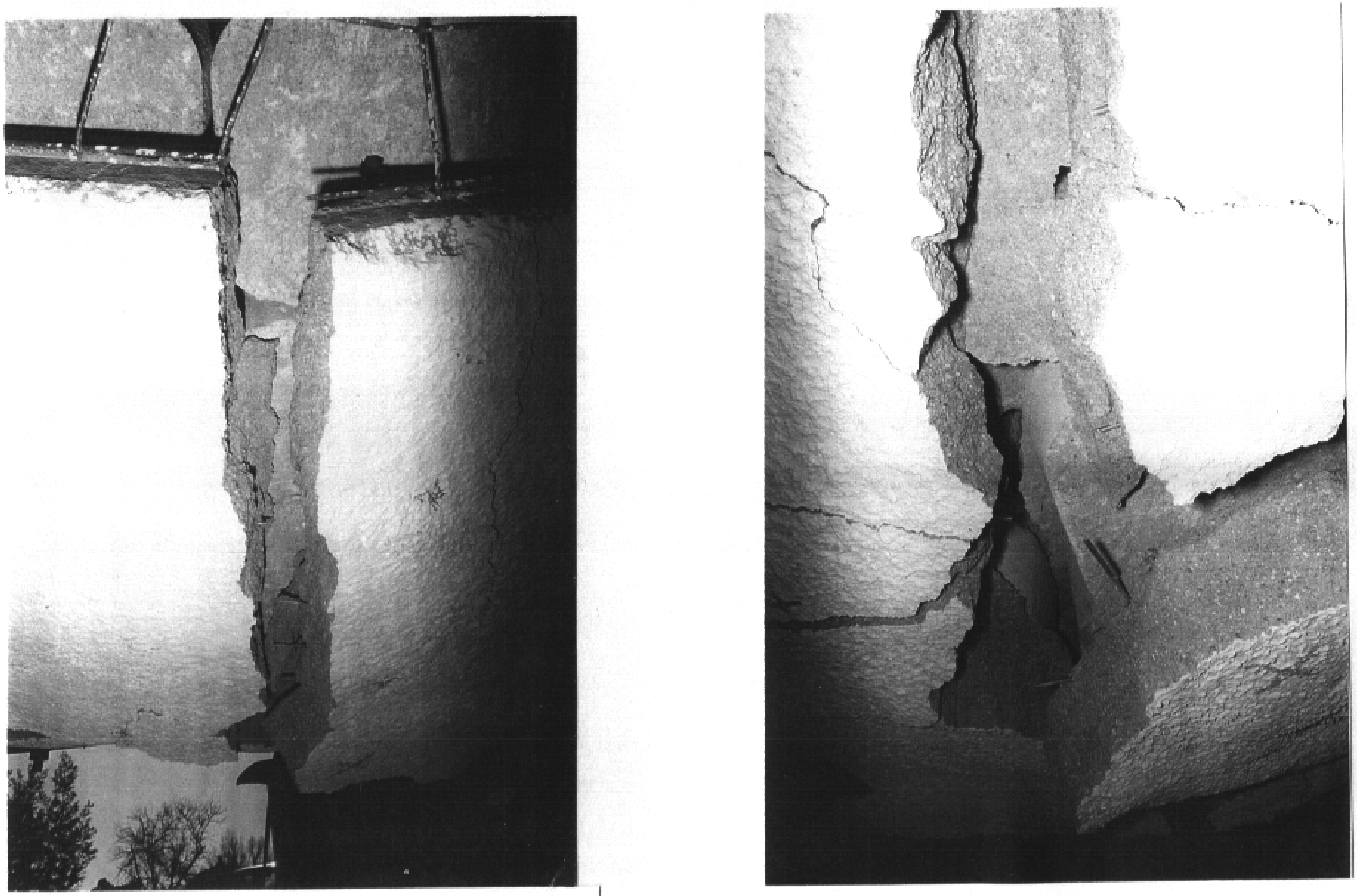


Photo 21: **Test No. 56. 448 mm deflection measured at centre point.**
Comprehensive failure of mesh caused massive spillout of concrete blocks on west side.

Photo 22: **Test No. 54. Impulse 50,5 kJ, 443 mm of deflection.**
Yielding loops slipped 346 mm at N-W, and 300 mm at S-W.



b) Detail of N-S crack, looking northward. Necking of wires can be seen.

a) Close view westward of main E-W crack. No wires left unbroken.

Photo 23: **Test No. 40. Impulse 15,4 kJ, 215 mm deflection.**
Detail of cracks in mesh reinforced shotcrete slab.

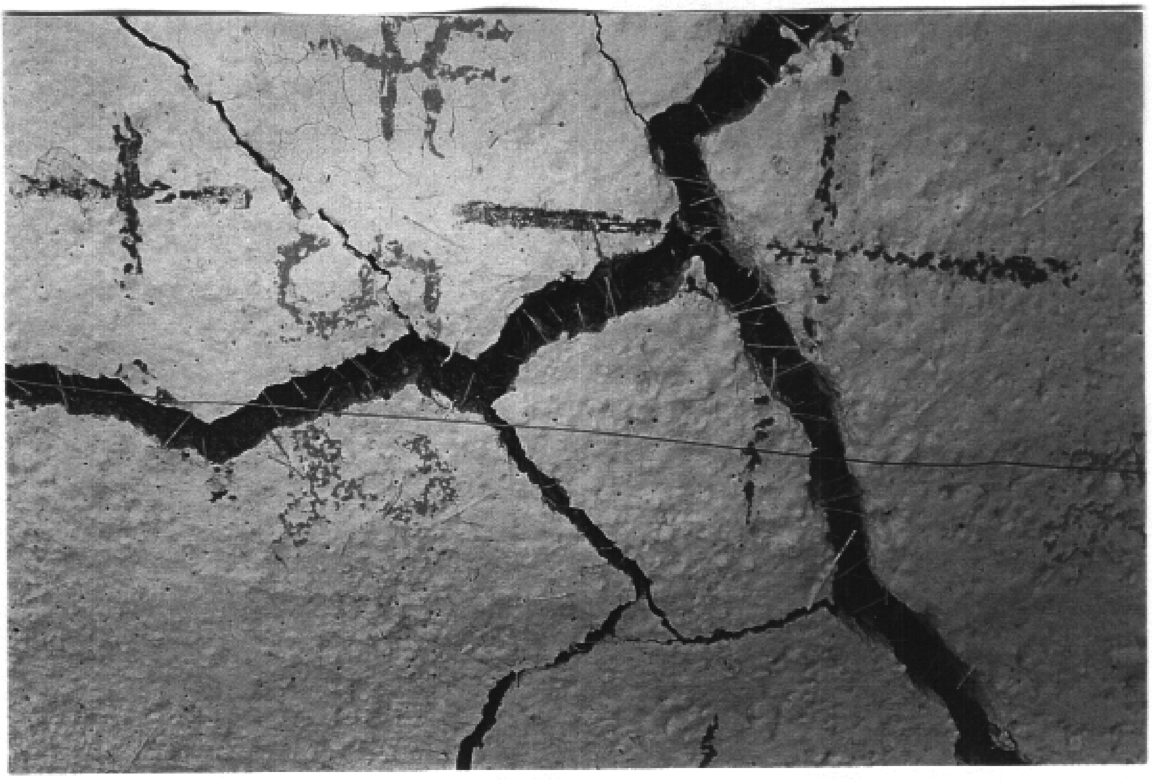


Photo 24: **Test No. 52. Impulse 10,3 kJ, 72 mm deflection.**
20 mm wide crack shows uniform distribution of 50 mm long polypropylene fibre.

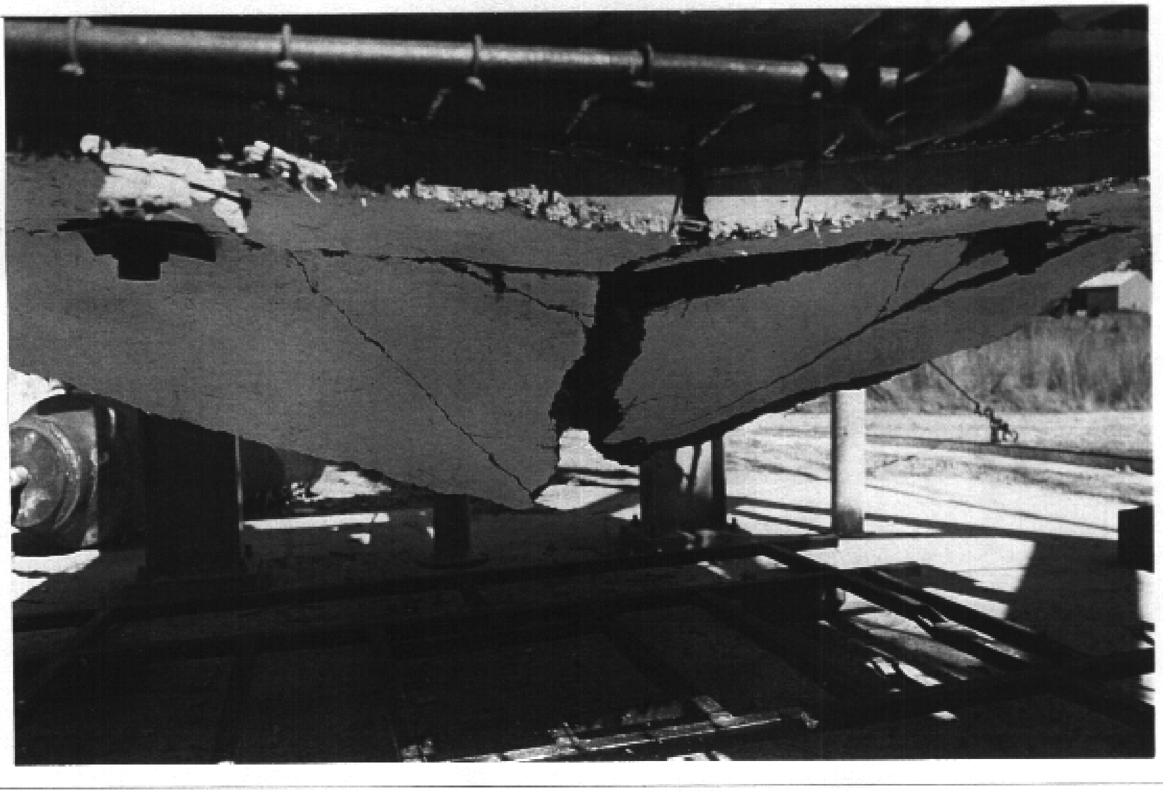
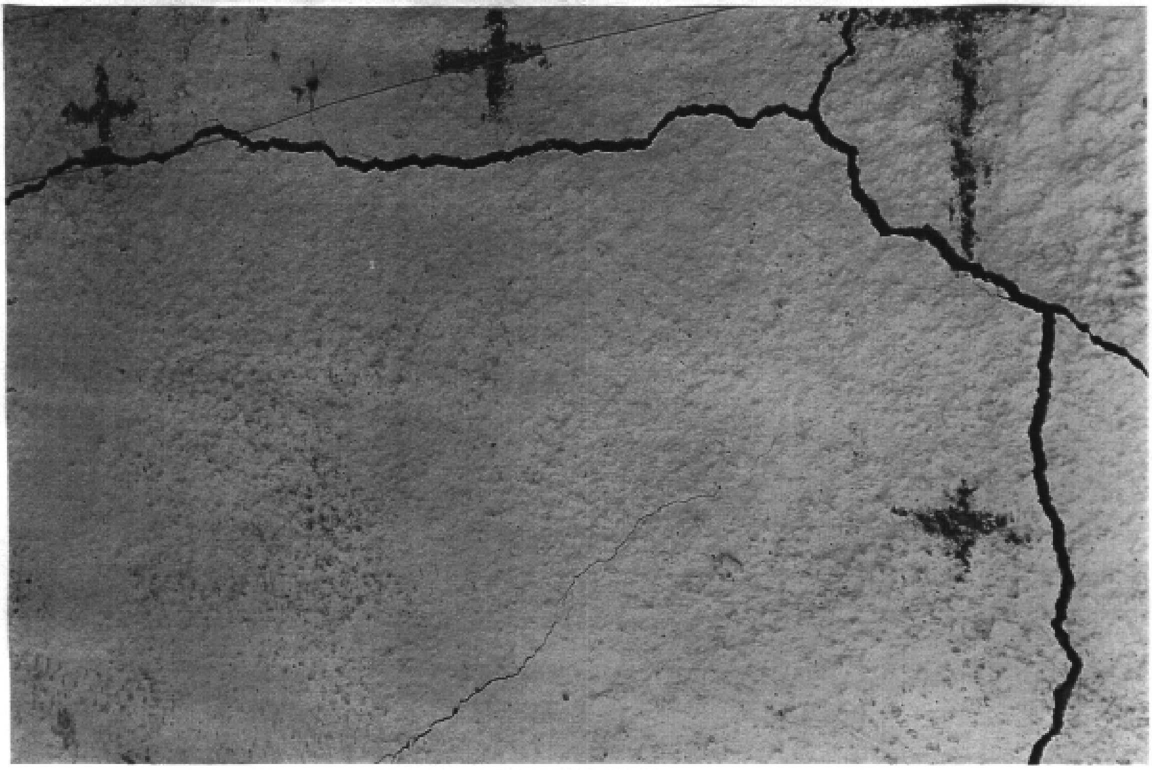
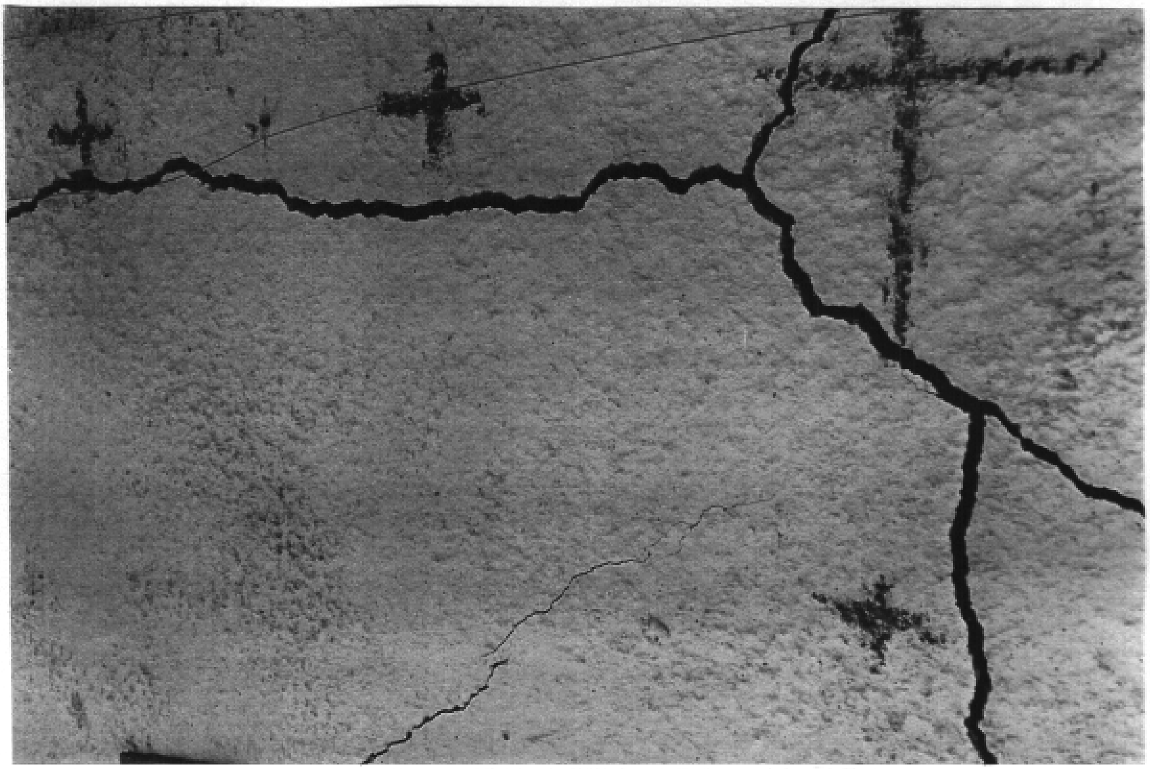


Photo 26: **Test No. 49. Impulse 15 kJ, 162 mm deflection after first impulse.**
Photograph shows view from North after second impulse of 7,7 kJ widened the crack from 75 mm wide to 200 mm wide.

Photo 25: **Test No. 50. Impulse 12,8 kJ, 97 mm deflection.**
Photo was taken shortly after impact when deflection was probably about half of the final 97 mm.



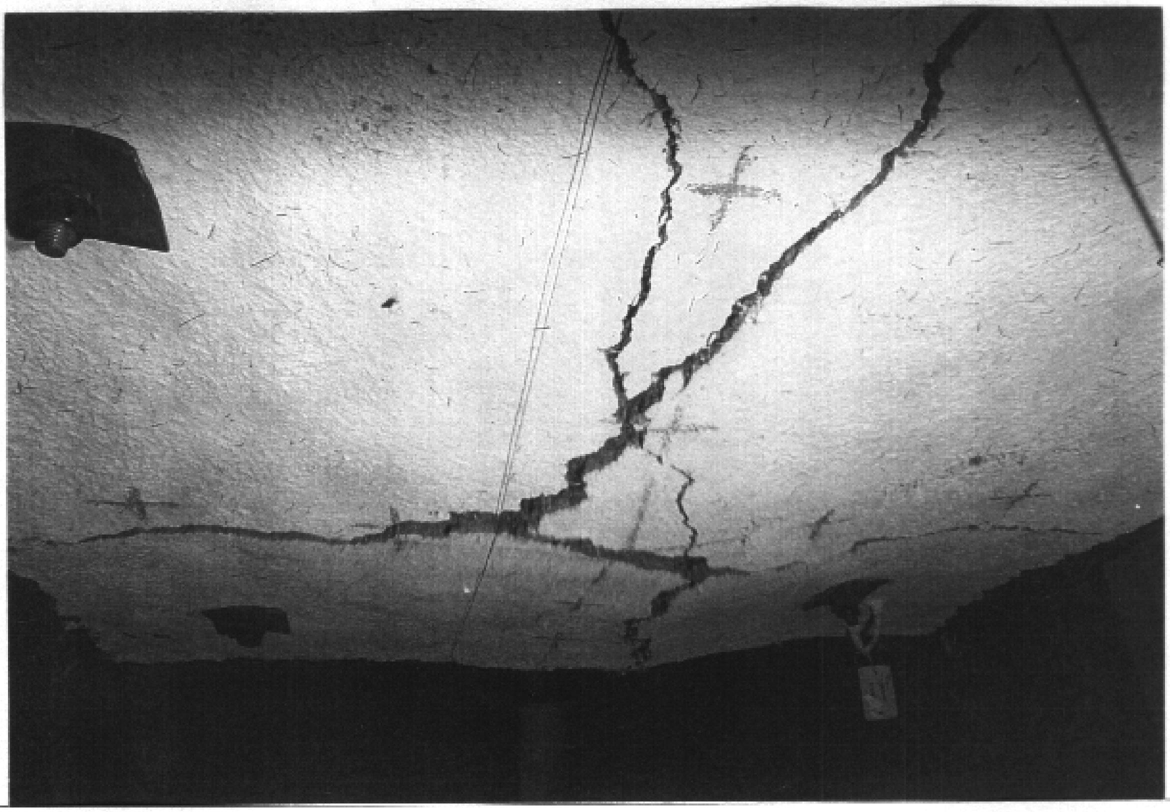
a) S-E quadrant after first impulse of 2,6 kJ. Crack from S-E does not extend to centre.



b) S-E quadrant viewed from north, after second drop of 1,5 kJ. Crack from S-E has extended very slightly.

Photo 27. **Test No. 41. Three impulses total 6,7 kJ, total cumulative deflection 38 mm.**

a) Shortly after first impulse of 15,4 kJ at impact velocity of 5,4 m/s causing about 30 mm deflection.



b) Shortly after impact of second impulse of 10,3 kJ which caused 223 mm deflection and increased crack width to about 75 mm.

Photo 28: **Test No. 48. Three impulses totalling 30,7 kJ caused complete collapse.**

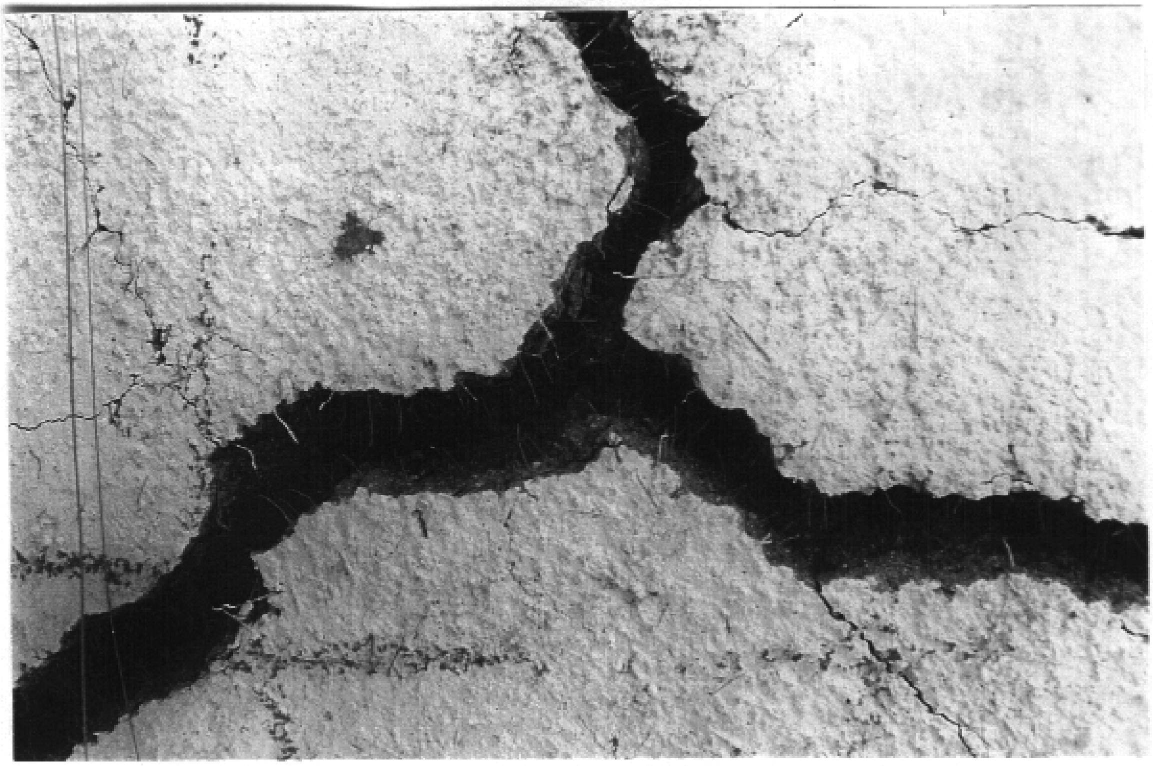


Photo 29: **Test No. 42. Three impulses each 10,3 kJ, cumulative deflection 378 mm.** Close view of centre of slab after second impulse of 10 kJ. Crack about 40 mm wide shows uniformity of distribution of 30 mm long Dramix steel fibre.