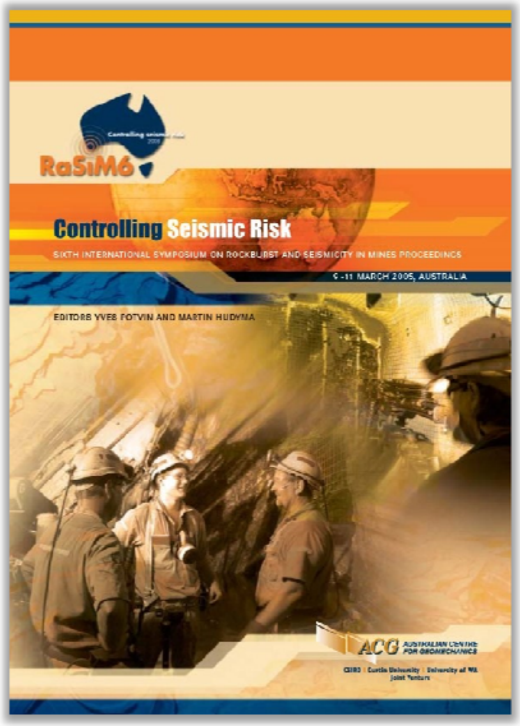
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Static and Dynamic Load-Displacement Characteristics of a Yielding Cable Anchor—Determined in a Novel Testing Device

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Conventional fully-grouted cable anchors used in the support of massive hard-rock excavations can be subject to abrupt tensile failure where wall rock displacements are large or dynamic.

A simple means to prevent this kind of failure has been developed by Duraset in association with SRK Consulting. The principle utilized to provide a standard cable strand with dynamic capacity is described in this paper.

In order to accommodate unusually long grouted tendons in available laboratory facilities, a special testing apparatus was devised. The principle of operation and method of construction is briefly described and preliminary results in both static and dynamic mode, are presented.

1 INTRODUCTION

When a moderate to severe seismic event occurs near to a rockbolt - supported mine tunnel, the intensity of rockburst damage that will result will depend on a multiplicity of factors. It is evident that the most important of these will include the magnitude of the seismic event, the proximity of the excavation and the condition of the surrounding wall-rock (this will determine the 'site response') and the design and quality of installation of the support.

It is generally accepted that no economic or practicable density of stiff or fully-grouted rockbolts or supporting tendons can withstand the effects of the strong ground motions accompanying a severe rockburst. Where thick rock slabs are ejected with velocities of up to 3 ms^{-1}, conventional rockbolts or cables will certainly fail in tension. Details of damage to excavations and support after a severe rockburst in a large base-metal mine in Canada are given by Simser et al. (2001). A degree of 'yieldability' or compliance is required in the tendons to enable them to survive the high transient loading of the rockburst while maintaining a substantial resistance to the movement of the excavation walls.

The principle of operation of one simple but effective means of providing rockbolts with the desired dynamic capacity, was described in a paper published in the proceedings of RaSiM5 by Ortlepp et al. (2001), p.263-266. Recently, the principle has been adapted to give cable anchors similar performance capability for larger mine excavations which may be threatened by rockbursts.

This paper compares the static and dynamic capacities of the Duracable with the performance of standard 15.2 mm diameter strand cable under simulated realistic conditions.

Because conventional cable anchors are often provided with an extendible 'free' or de-bonded length nearest the excavation, proper simulation in the laboratory requires testing of specimens of a few to several metres in length. There is no dynamic testing machine available in South Africa which can accommodate embedded cable test specimens longer than about 1.2 m overall length.

In order to overcome this serious limitation, a simple and robust displacement-conversion device was designed which would utilize the dynamic loading capability of the 300 kJ drop-weight stope support test facility which forms part of the SIMRAC research endeavour (Ortlepp et al. 2001 p.197). The rationale and design of this piece of apparatus is described in the paper and initial results are presented.

2 PRINCIPLE OF OPERATION OF THE DURACABLE

The Duracable has been developed to utilize the same principles of energy conversion and frictional resistance that underlie the design of the durabar – Ortlepp et al. (2001). In the durabar a sinusoidal 'wave' impressed into a smooth bar of ordinary low-carbon steel generates a large but controlled resistance to being pulled free from the annulus of hardened grout that anchors it in the surrounding rock. To retain the same degree of wave deformation in the springy, very high tensile wires of a single strand cable requires that the cable be sheathed with a length of close-fitting steel tubing of 2.5 mm wall thickness to form a sleeve over the anchoring length of the unit – Figure 1. In the manufacturing process the sinusoidal waves or crinkles are forcibly pressed into the sleeved portion of the cable anchor. The deformed mild steel sleeve then retains the crinkled shape that will ensure that the anchor is securely bonded to the rockmass by the surrounding grout.

The load-displacement characteristic of the Duracable is unaffected by the grout strength provided that it exceeds the necessary minimum of 25 MPa. The presence of the sleeve has the additional advantage that it allows a layer of lubricant to be provided between the fixed inner surface of the sleeve and the sliding surfaces of the strand wires. This ensures a very smooth and constant value of static 'yielding' resistance – see Figure 7.

When installed, the deformed sleeved end of the Duracable is anchored at the remote end of the hole with the entire remaining 'free' length left ungrouted or, more commonly, de-bonded by means of a close-fitting PVC sleeve in the fully-grouted hole – Figure 1.

In operation, excessive dilation of the rock surrounding the excavation or violent ejection of a large block or slab cannot damage the cable strand. Controlled sliding will occur in the crinkled portion before the transient load can reach values close to the breaking load, and thereafter the sustained resistance will slow down and control the rock movement.

Survivability is the all-important requirement of support design for high stress and rockburst conditions and this

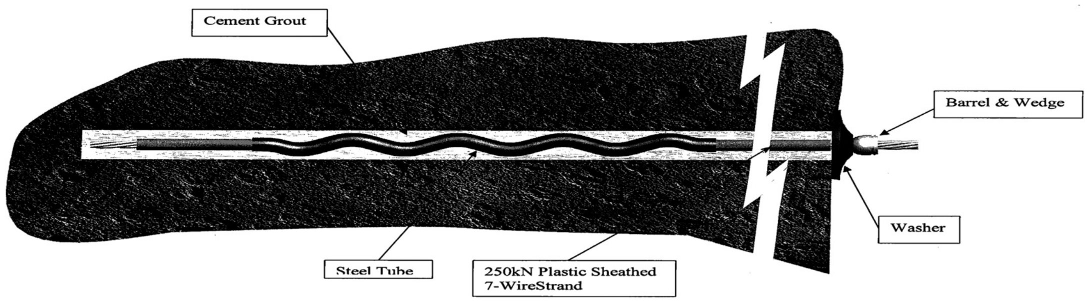

FIG. 1 Sketch of installed Duracable

can only be ensured if all elements of the system have adequate dynamic capability i.e. an in-built 'yieldability' or compliance.

3 DESCRIPTION OF DYNAMIC TESTING FACILITY

To measure the dynamic resistance of a support element, or to demonstrate its survivability, it is necessary to use an appropriate testing facility. It has to have the capacity to break conventional non-yielding elements in the same way as typically occurs in actual rockburst conditions underground.

The wedge-block loading device was developed because available testing facilities had limitations. The first was the limited length of specimen which could be accommodated. Currently, the maximum length which can be tested dynamically in South Africa is 1.2 m. This leaves insufficient length for good anchorage of the test length of cable and makes it impossible to simulate a 'free' length in the installed anchor.

Other drop weight testing devices are not stiff enough to simulate the rockmass. This can lead to wrong assessments of survivability of support tendons.

The wedge-block loading device consists of two guided thrust-blocks with inclined faces (somewhat like book-ends) with a wedge driving them apart – see Figure 2. The wedge converts vertical displacement into horizontal displacement. Thus tendons longer than 5 m can be tested dynamically. Ensuring sufficient lateral stiffness of the pipe specimen holder which simulates the surrounding rockmass, prevents it from bowing under axial load

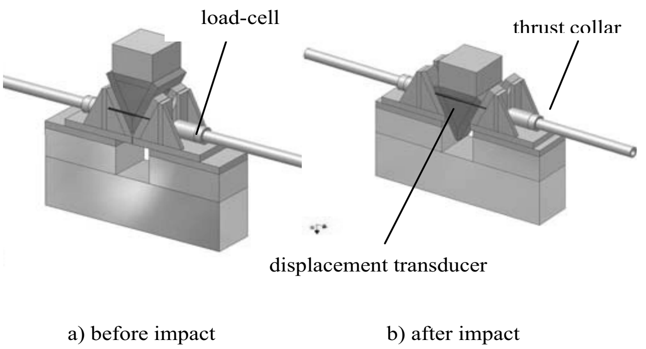

FIG. 2 Isometric views of wedge-block loading device

The hollow bar from which the specimen holder is made has an O.D of 80 mm and an I.D of 50 mm. When single-embedment testing is done e.g. when a standard single-strand anchor with a free length of 2.0 m is tested, the 1.5 m long extension tube that surrounds the unbonded length has dimensions of 71 mm O.D and 45 mm I.D giving it an axial stiffness of 0.27 MN/mm. This is considered to adequately represent the compressibility of the partly-relaxed rock surrounding a hard-rock excavation.

FIG. 3 Photo of wedge loading device in position under testing machine

The load and displacement experienced by the tendon are captured via electronic monitoring devices. The results can then be analysed to determine the 'exact' energy consumed during the test or at breakpoint rather than a derived value.

The energy can either be applied quasi-statically with a compression testing machine as shown in Figure 3 or dynamically with a drop weight. The mass of the drop weight is 10 000 kg. The height of the drop can be altered from 0.4 m to 4.0 m. This flexibility can be used to study effects of speed and/or momentum transfer on tendon or test method performance. The maximum energy available in the current setup is 400 kJ at an impact velocity of 8.9 m/s.

4 TEST PROGRAMME

Before embarking upon an extensive testing programme, it was considered necessary to show that the wedge-block loading device and monitoring facility had the desired performance capability. At the same time we hoped to discover how much modification to the prototype Duracable was required to develop its potential.

TABLE 1 Detail of tests conducted

Test No	Type of Anchor	Mode of embedment	Free Length	Loading Rate	Result (energy absorbed)
#1	Standard single-strand	Double-bulbed 1.2 m cement-grouted	2.0	3.2 ms^{-1} impact velocity	Cable broke at wedge-barrel. Recording failed. (energy ?)
#2	Standard single-strand, fully grouted	1.2 m cement-grouted, double embedment	Nil	7.0 ms^{-1} initial maximum	Cable broke at 300 kN after 26 mm displacement. (3.1 kJ)
#3	Duracable	Cement-grouted	Fully de-bonded	11.0 ms^{-1} initial maximum	Cable intact after 220 mm displacement. (19.3 kJ)
#4	Duracable	Cement-grouted	Fully de-bonded	0.0005 ms^{-1}	Maximum load 100 kN steady-state 70 kN. (13.9 kJ)

The limited preliminary test programme consisted of lengths of 15.2 mm dia single-strand cable which were cement-grouted into the steel tube specimen holders described above, in the configurations listed in Table 1.

5 RESULTS

The load in the specimen was measured by means of a wire resistance strain-gauged load-cell forming a hollow cylinder placed between the 'book-end' and a thrust-collar on the thick-walled tube forming the specimen holder – see Figure 2. Displacement was monitored by a 250 mm linear displacement resistance transducer.

The data was captured by means of a Spider 8 data acquisition unit using CatMan monitoring and analysing software. Test #2 was sampled at 1600 Hz and plotted in Figure 4 at 533 Hz. Test #3 was sampled and plotted in Figure 5, at 1200 Hz and the static Duracable test #4 was sampled and plotted at 50 Hz in Figure 7.

6 DISCUSSION OF RESULTS

6.1 Conventional Single-strand Anchor – 2.0 m Free Length

In the support of underground excavations it is common installation practice to leave a length of the cable anchor closest to the collar of the hole de-bonded from the rock. The extensibility of the 'free length' allows tension to be applied to help seat the tapered wedges in the steel barrel at the base-plate. It also provides some resiliency to protect against seismic and dilationary over-loading.

Invariably, failure will occur at the stress concentration where the serrated teeth of the wedges bite into the outer wires of the cable strand. There will be a consequent reduction in the ultimate load and ductile elongation of the anchor compared with expectation based on manufacturer's laboratory-determined static tests. The extent of this reduction in performance could not be determined because a triggering failure in the monitoring system meant that no measurements were recorded.

6.2 Single-strand Fully-grouted Anchor – Figure 4

With no free length available, the suppliers' rated 0.9% elastic elongation limit of 235 kN and ultimate tensile strength of 260 kN were exceeded after 12 mm and 23 mm of opening between the butted ends of the steel test-piece holders. The amounts of energy absorbed by the failing cable were 2.1 kJ and 4.6 kJ respectively. The mode of failure of the individual wires was the characteristic 'cup-and-cone' observed in the abrupt fracture of cable anchors after rockbursts. These very low values of energy compare with those of a standard fully-grouted reinforcing bar – see Ortlepp et al. (2001) and demonstrate how vulnerable fully-grouted tendons are when rockbursting is a threat.

6.3 Duracable, Dynamically-loaded – Figures 5 and 6

A close examination of the time history of load change (Figure 6) shows that it required about 1.5 milli-seconds after impact for the load in the Duracable to increase to about 100 kN before sliding commenced and the load dropped to below 50 kN.

During the following 10 milli-seconds, in a series of four fairly-constant 'stick-slip' steps the resistance increased incrementally to 125 kN. Thereafter the resistance to further displacement fluctuated widely between 10 kN and 140 kN with two peaks of 180 kN and 230 kN. A likely explanation for this 'stick-slip' behaviour is that the lubricant between the enclosing sleeve and the strand wires probably evaporated during the first 65 mm of displacement (which occurred at a velocity of 7.5 ms^{-1} and an energy dissipation rate of 680 kW). Thereafter friction-welding occurred at the helical line contacts between steel wire and steel sleeve. It requires a high peak load to break each welded contact and allow the individual wire to slide again, causing the load to drop. The renewed sliding occurs very rapidly, generating enough frictional heat to re-weld the contact almost immediately, resulting in the next rapid increase in load.

With the entire displacement of 220 mm occurring in just 60 milli-seconds it is considered that there is insufficient time for the high contact temperature to penetrate deep enough into the cable to affect its overall strength. Thus we are not greatly concerned with the fluctuating nature of the resistance load. Importantly, the cable anchor survived this potentially damaging energy pulse and, after the controlled total displacement of 220 mm, re-established a final resistance load of 80 kN – Figure 6.

Further development and testing is necessary to determine to what extent the dynamic capacity of the 'yielding' mechanism can be increased before continued breaking of the friction-welds causes permanent damage to the cable-strand wires.

In its practical application, this means that a Duracable-supported excavation could survive a severe rockburst, provided that the rest of the support system had matched capability. After the event, the main support elements should still possess sufficient dynamic capacity to protect the damaged excavation walls against further seismic threat.

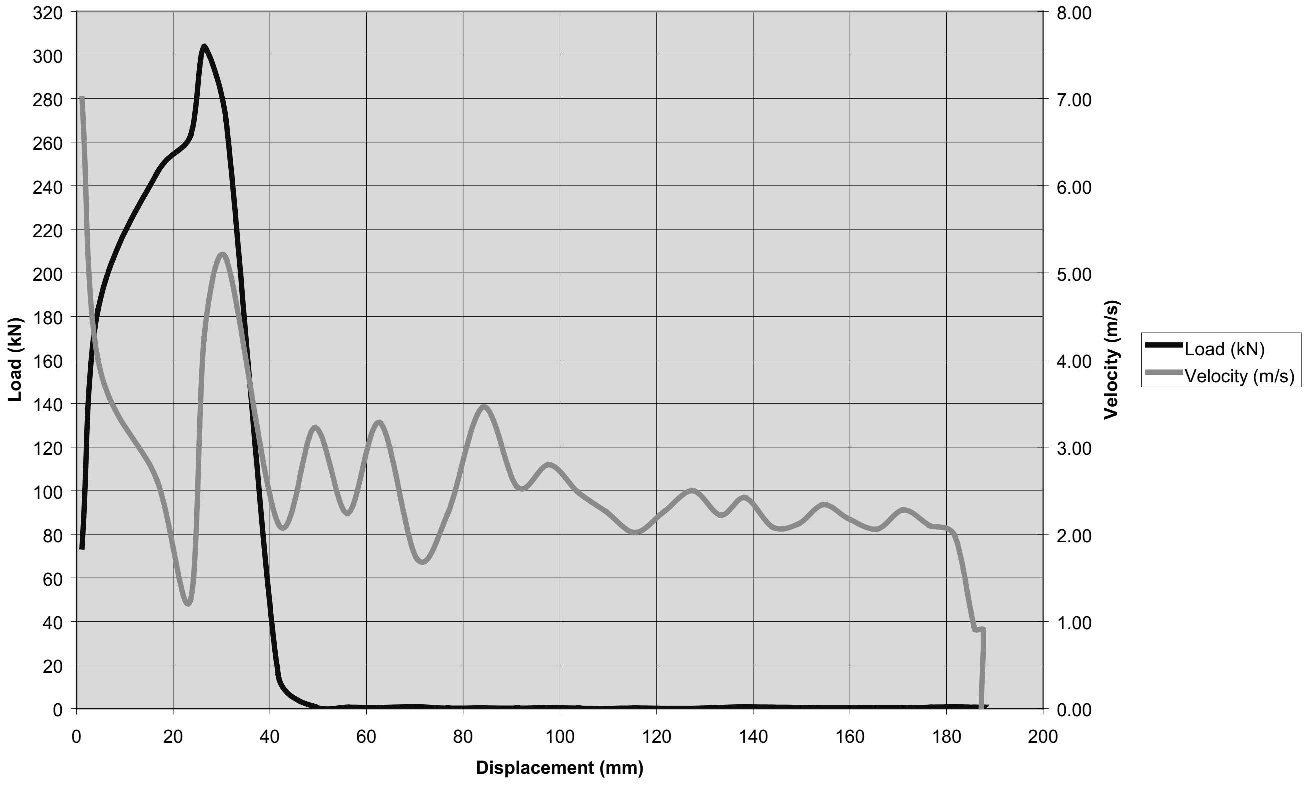

FIG. 4 Test #2 – dynamic loading of fully-grouted 15.2 mm strand

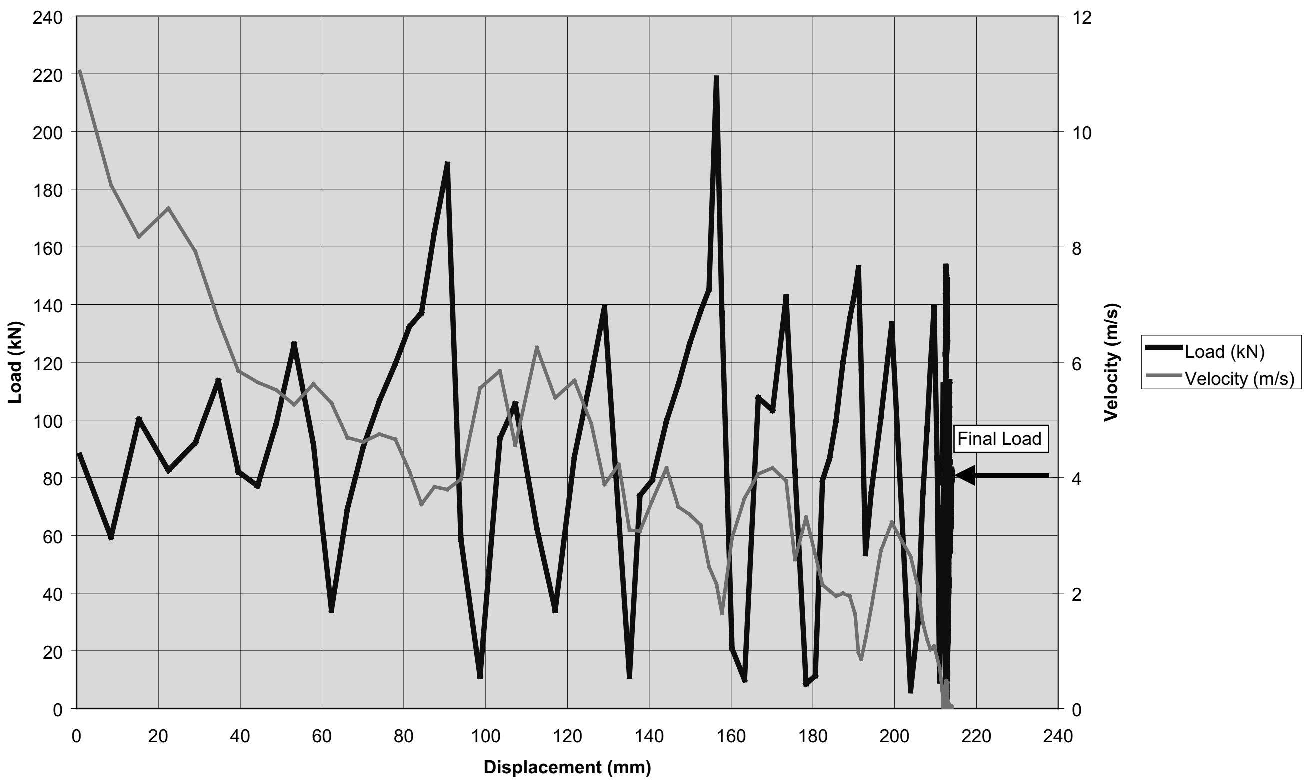

FIG. 5 Test #3 – dynamic loading of 15.2 mm Duracable

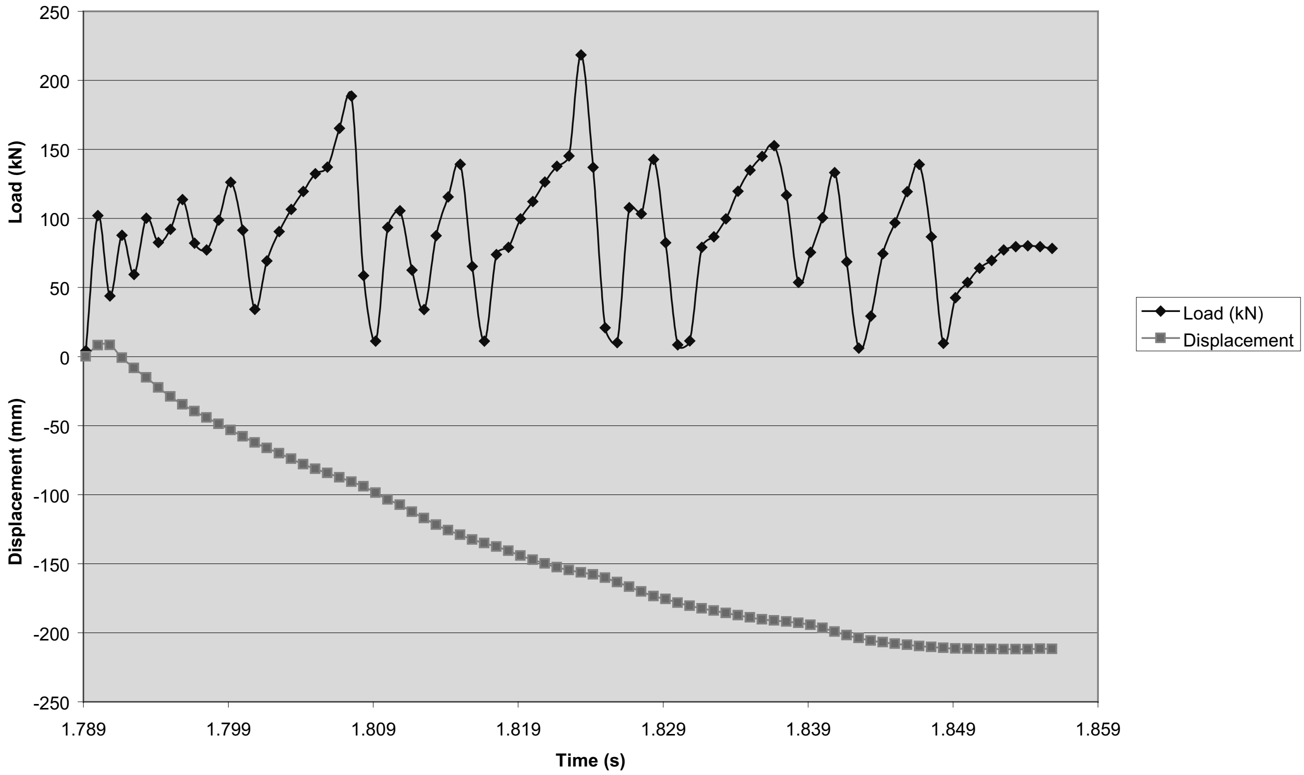

FIG. 6 Graph of load and displacement against time for Duracable test #3

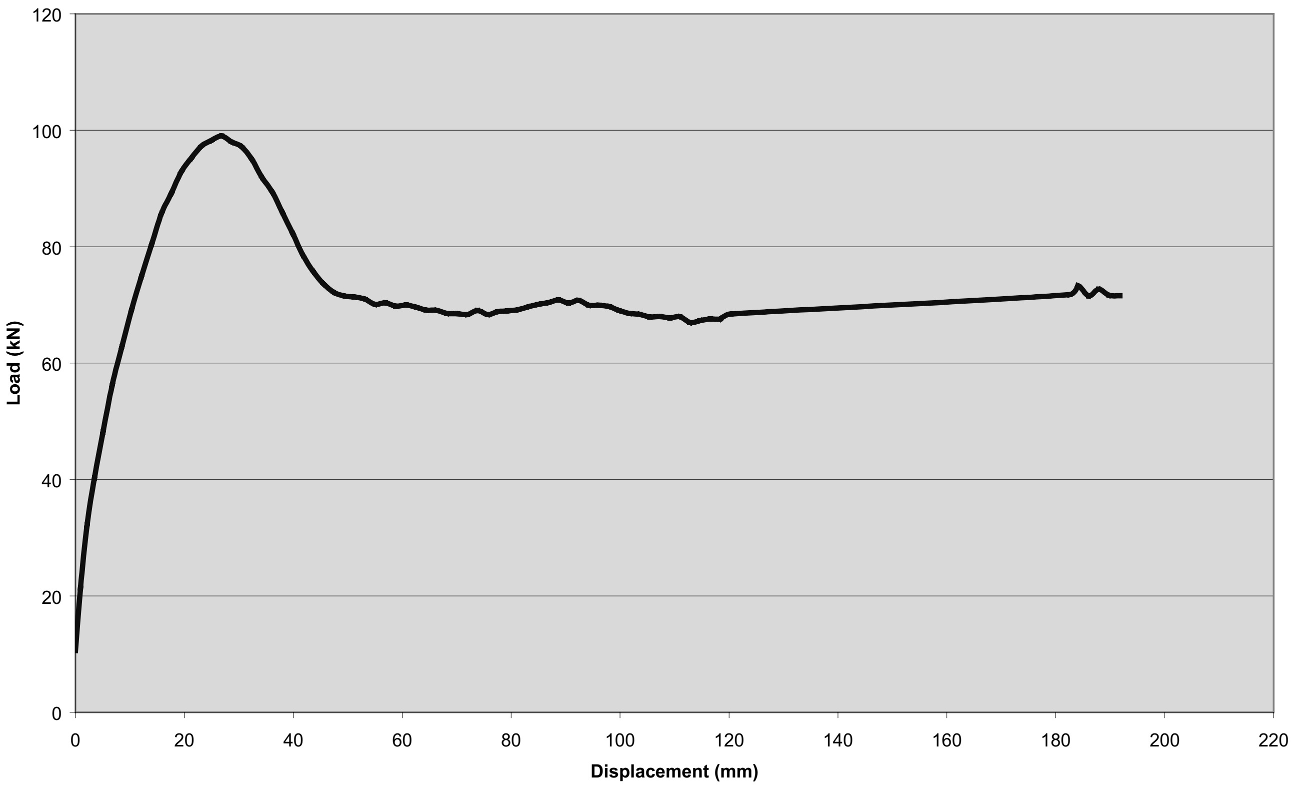

FIG. 7 Test #4 – Slow-rate loading of 15.2 mm Duracable

6.4 Duracable – Static Test – Figure 7

Under quasi-static loading conditions the Duracable displayed a particularly smooth response with the resistance rising to 100 kN before sliding commenced. After some 45 mm of yield the resistance load dropped to a steady value of 70 kN, consuming energy at 7 kJ per 100 mm of displacement. After 190 mm of displacement the test was stopped with the anchor's dynamic capability unaffected.

Because of the internal lubrication and the relatively precise manufacturing control of the sliding mechanism, there is little doubt that the performance of individual units will be very consistent. It is also likely that the resistance load value will be insensitive to variation in displacement rate within the range where temperatures at the sliding surface remain reasonably low.

To utilize the potential strength of single-strand cable to better effect it is evident that the yield load value of the present Duracable needs to be increased substantially. This is easy to achieve in principle and further development in this direction is under way.

7 CONCLUSION

Although only a few tests have been done so far, several conclusions can be confidently asserted.

- The wedge-block loading apparatus is a relatively cheap and convenient device for testing long grouted anchors.
- When used together with a suitable drop-weight facility, it is a very effective way of imposing transient loading at high displacement velocities on various types and lengths of tendon support.
- The essential principle of preventing tensile failure of a tunnel support tendon by allowing controlled sliding at loads below the failure limit, works as effectively in the Duracable as it does in the solid Durabar rockbolt.
- Under slow-loading conditions, the Duracable response is very smooth and consistent.
- It is able to survive very high strain rates (>11 ms^{-1}) under dynamic loading conditions, without incurring any material damage.

Further tests are planned to examine the 'stick-slip' load fluctuations at more moderate displacement rates in the range of 3 ms^{-1} to 5 ms^{-1}. Further development work will be done to determine the best way to increase the quasi-static level of load resistance.

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