Dynamic Testing of Threadbar used for Rock Reinforcement

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ABSTRACT: A comprehensive axial test program has been undertaken at the Western Australian School of Mines (WASM) Dynamic Test Facility on the performance of 20mm threadbar. The threadbar tests had a double embedment configuration, with variation to the encapsulation lengths, debonded length and surface hardware and fixtures to examine failure mechanisms. Performance was significantly affected by the collar embedment length and type of fixture nut used. Results ranged from thread shearing occurring between the nut and bar at 1kJ of energy dissipated, to plastic deformation of a central debonded length dissipating 22kJ.

1 INTRODUCTION

Threaded bar has a long history of use in civil engineering projects, particularly for long ground anchors where the ability to join short straight lengths is achieved using thread couplers. Threadbar is also widely used in mining applications for the control of static and dynamic loads. Threadbar may also be referred to as rebar or Gewi bar, a proprietary product developed by Dywidag Systems many years ago.

The effects of changes in embedment lengths and surface fixtures on the performance of 20mm threadbar to dynamic loading are investigated. The Western Australia School of Mines (WASM) Dynamic Test Facility (Player et al. 2004, and Player et al. 2008)) has been used to quantify the performance of threadbar.

1.1 *Dynamic Loading Model*

The WASM model uses the double embedment test configuration to examine the performance of complete reinforcement systems subject to dynamic loading. The philosophy is to examine the failure criteria for reinforcement systems in response to a single axial dynamic load. This is achieved by dropping a complete reinforcement system (tensioned were applicable) with a loading mass integrated with the collar embedment length into a pit. At the toe of the reinforcement system a stiff steel beam that straddles the pit and impacts onto two short displacement high deceleration buffers. The momentum of the loading mass must be dissipated by the reinforcement system or it will fail. The load is transferred to the surface hardware and to the reinforcement bar through the simulated borehole, and the encapsulation medium. The loading mass and the impact energy can be adjusted to give the desired initial energy. The standard impact uses a 2tonne collar load and 6m/s impact velocity onto the buffers.

A brief description of the WASM test facility and schematic of the test configuration is described in Section 4 of Player et al. 2009 (this conference). The WASM Dynamic Test Facility and comparisons to other mining dynamic testing facilities is examined in detail by Player et al. (2008).

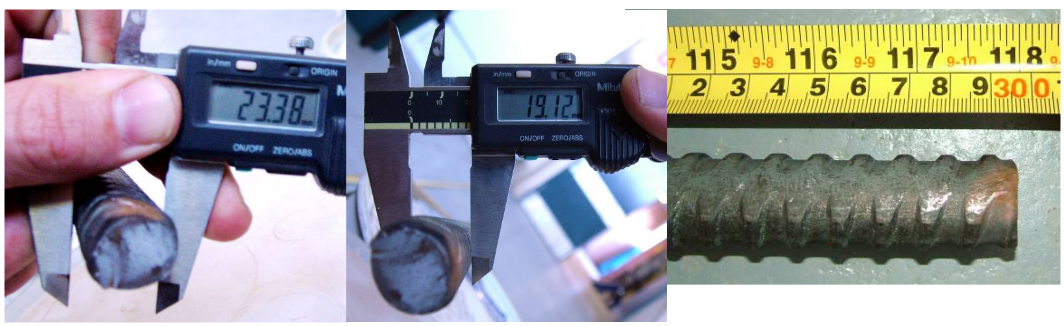
2 THREADBAR REINFORCEMENT SYSTEM

Cement grout or resin is used to encapsulate the threadbar in a borehole drilled in rock. The elongation capacity of the overall reinforcement system may be increased by creating a free length between the toe and collar regions of the bar; either by having a short encapsulation length at the toe end or by decoupling the bar from the encapsulation medium. The latter method is preferred as it provides better resistance to shear movement across the axis of the borehole. The collar fixture comprises a domed plate, spherical washer and nut; the latter two components maybe integrated as one item.

WASM static and dynamic tests are carried out under axial load conditions, and are not necessarily representative of the shear loading that can occur underground. Shear loading of a reinforcement system underground is particularly uncertain. The performance will be significantly affected by the quantity of available dilation on the shearing structure, how intact the rock remains that is applying the shear loading, the rate of debonding / fracturing between the threadbar and encapsulation medium. An important influence for performance is whether the shear displacement is concentrated at one location on the bolt, or multiple locations. Concentrated shear will result in failure at a smaller displacement.

2.1 *Static Properties – 20mm threadbar*

The threadbar used in all tests was a standard 20mm diameter product, common to the Australian civil and mining industries; the bar has a coarse 10mm pitch thread (Figure 1).



On the outside of the threads Across the flat

Figure 1 : Threadbar diameters.

The mechanical properties, and the test configurations required to obtain these, are specified by Australian Standard 4671:2001, Steel Reinforcing Materials. The physical and mechanical properties are given in Table 1.

Table 1 : Physical and mechanical properties of 20mm threadbar.

	Minimum	Average
Core Diameter (mm)	19.3	19.5
Cross Sectional Area (mm2)	293	299
Yield Strength (MPa)	500	550
Yield Force (kN)	147	165
Tensile Strength (MPa)	600	640
Tensile Force (kN)	175	191
Elongation (%)	12	21

2.2 *Reinforcement System Configurations*

Three embedment configurations for the 20mm diameter threadbar were examined; fully encapsulated, centrally debonded and jumbo installed with a toe anchor. The testing also involved various collar plate, washer and nut combinations. The embedment configurations are used by the mining and / or civil engineering industries predominately for static loading conditions. Due to the wide application of the threadbar system it was considered worthwhile to develop an understanding of its dynamic capability.

Threadbar when fully encapsulated and loaded by the displacement across a single discontinuity, will have load transferred as summarized in Figure 2. The effective load transfer rate and hence system performance will be influenced by the components shear strengths, strain rate capabilities, and the interface conditions between the steel, grout and rock.

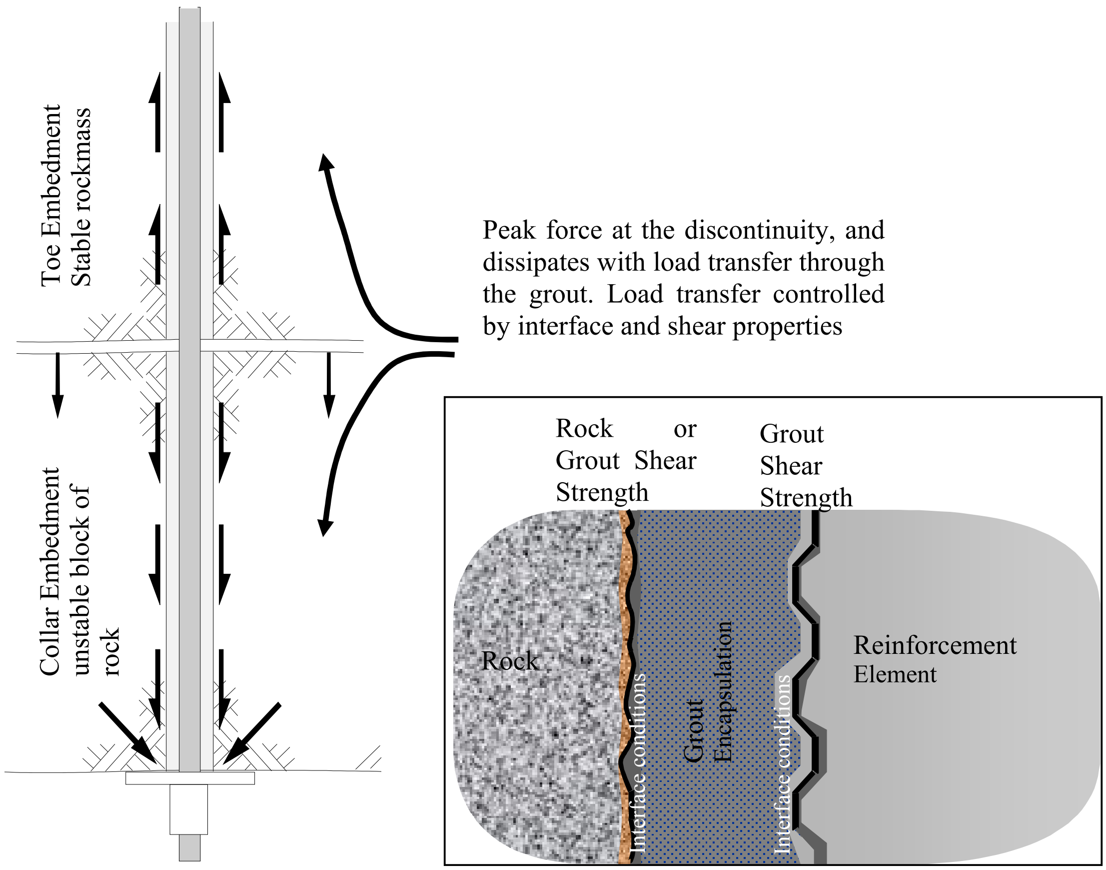


Figure 2. Load transfer controls for fully encapsulated threadbar.

2.3 *Fully Bonded Threadbar – Encapsulated in cement grout*

The threadbar used in the fully encapsulated tests were hot dip galvanized and encapsulated in a 0.45 water / cement ratio grout with 0.2% Methocel to control segregation of the grout. The threadbar was pushed through the grout filled thick wall pipe and centered within the grout column. The pipe had a 49.5mm internal diameter and 60mm external diameter, with an equivalent radial rock stiffness modulus of 49GPa (Hyett et al., 1992).

The threadbar was 2.4m in length, and all samples were configured to have a 1.0m collar section, Figure 3. Due to variations on installation, the exposed collar length from the pipe varied between 0.1m and 0.2m, to give toe embedment lengths of 1.2m to 1.3m. Collar embedment remained at 1.0m. Surface hardware consisted of 150mm square 8mm thick dome plate, washer and 32mm long mine nut (T20 x 10.0 pitch LH thread). The nut was tensioned with a torque wrench when the sample was setup in the test facility. A load cell was used between the nut and dome ball washer when space allowed.

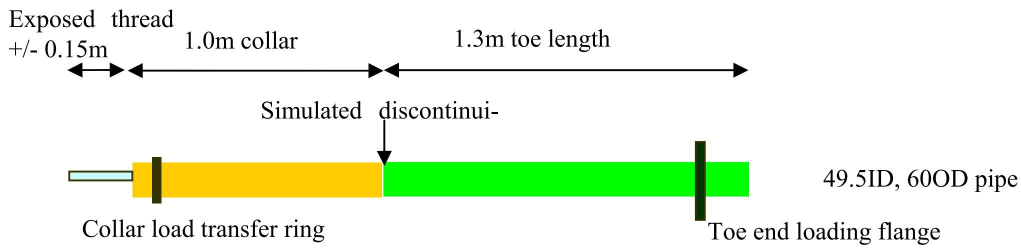


Figure 3. Sample configuration for dynamic testing.

Testing was carried out a minimum 28 days after grouting; one sample was tested five years after grouting. Wood (1992) showed for air-cured concrete samples that a consistent strength was obtained after 28 days to greater than 5 years. An assumption from the long running research program is made that the WASM undercover stored samples are equivalent to somewhere between air-curing (21-24°C, 50% humidity) and outdoor (large temperature range, rain exposure, partially buried). Therefore the compressive strength and modulus of the grout are not significantly different at 5 years compared with 28 days. These parameters are used for a proxy for the fracture and cracking properties of the grout in the absence of other data.

Reactivity between the zinc coating and concrete has been extensively reviewed in the book by Yeomans (2004). The zinc coating is stable in the pH range 6-13 and passivation occurs quickly in wet concrete with the formation of a protective film. However, threadbar will be passivated if left for four to six weeks exposure to the atmosphere after galvanization prior to installation into concrete. The reaction of zinc in concrete, passivisation at high or low pH, produces hydrogen through a complex chemical reaction predominantly while the concrete mix is wet.

A parameter that maybe more important and difficult to quantify is the interaction between the grout and the bar; as the bar is pushed into the grout, the contact layer will draw slightly more water out of the grout mix due to movement of the bar into the grout. This will make the contact layer slightly weaker than the main core of the grout. The processes by which the grout / concrete can be failed by the deformation on a threadbar hence leading to excessive displacement are described in Chapter 8 of Yeomans (2004). The discussion "*shows that bond strength is not a single value….it is a variable that depends on many factors, among which is the mode of failure…..The mode of failure is also dependent upon several factors, which include cover depth, the concrete strength, the reinforcement size, the presence of coatings on the steel, the size of the concrete member and the confinement of the main reinforcement*."

2.4 *Partially Debonded Threadbar - Encapsulated in cement grout*

The debonding provided a significant free length that was available to stretch and dissipate energy under dynamic load when compared with the fully encapsulated threadbar. The partially debonded threadbars were non-galvanised, nominal 3.0m in length, and the PVC tube clamped on the central 1.6m of threadbar, Figure 4.

The grout was prepared with 0.40 - 0.45 water / cement ratio and tested between 22 and 56 days. The unconfined compressive strength determined from tests on cylinders was >40MPa in all cases. The thick wall steel pipe has the same dimensions as the fully encapsulated threadbar configuration. The simulated discontinuity was located at a standard 1.0m from the collar.

Two surface hardware configurations were tested. The first used a separate 32mm long mine nut (T20 x 10.0 pitch LH thread) and dome ball washer. The second was an integrated nut and dome ball washer with a continuous thread 45mm in length. Both types of test used a 150mm square 8mm thick dome plate, Figure 5.Due to variations in installation the follow configurations where tested, as per Table 2.

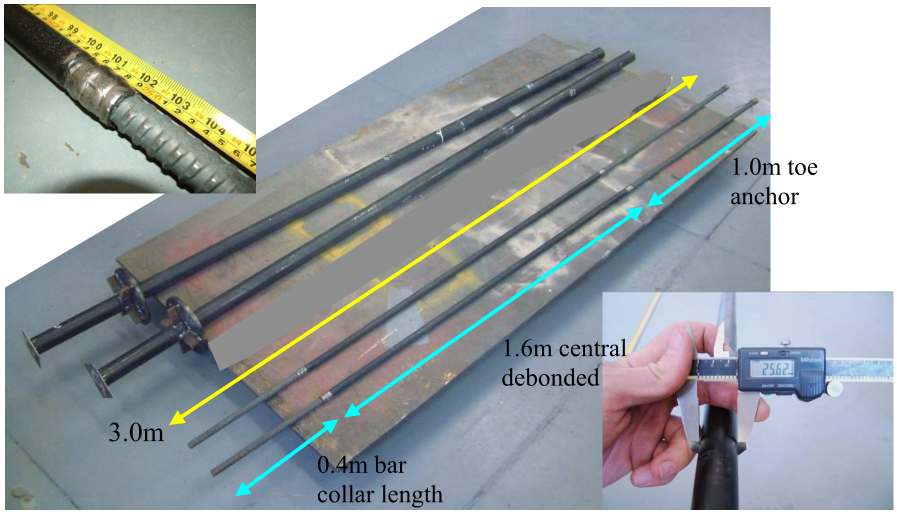


Figure 4. Debonded threadbar geometry.

Figure 5. Surface hardware used on debonded threadbar.

Table 2. Debonded threadbar test configuration.

Bolt #	Exposed Collar of the bolt* (mm)	Embedded collar (mm)	Debonded Length (mm)	Embedded toe length (mm)	Nut Type
83	213	187	1600	1000	Mine
84	172	240	1600	1000	Mine
85	141	249	1605	995	Integrated
86	162	238	1615	945	Integrated

*Exposed collar thread also includes where the grout has not reached the end of pipe.

2.5 *Resin Encapsulated Threadbar Installed by Jumbo - toe anchored*

Resin encapsulated galvanized threadbar of 2.4m length were anchored at the toe into rough simulated boreholes. The simulated boreholes were taken underground and a drilling jumbo was used for installation. The simulated boreholes were of appropriate internal diameter and are described by Player et al. (2009). All used a simulated discontinuity at 1.0m from the collar. Effective resin mix was achieved from the mechanism attached to the threadbar. The simulated borehole suffered from resin bleed through the end of the sample or from the bolt pushed too far into the hole and breaking out the stop plate on the simulated borehole. This reduced the length of anchor encapsulation and increased the length of unbonded bar at the collar of the hole as detailed in Table 3. It allowed the assessment of variable toe anchor lengths to determine if there was a minimum encapsulated length that would change how the bolt performed under dynamic load.

Table 3. Toe anchor resin encapsulated bolts

Bolt #	Unbonded Collar Length (m)	Toe Encapsulated Length (m)	Tensioned surface hardware
124	~1.5	~0.81	Jumbo
125	~2.1	~0.24	Jumbo
126	~1.6	~0.73	Lab / torque wrench
127	~1.9	~0.51	Lab / torque wrench

Surface hardware consisted of an 8mm thick domed plate, dome ball washer, low friction washer and nut. Two of the samples were installed by the jumbo (Figure 6), with the simulated borehole underground. The other two had the surface hardware installed with a torque wrench, to allow the use of a load cell at the collar.

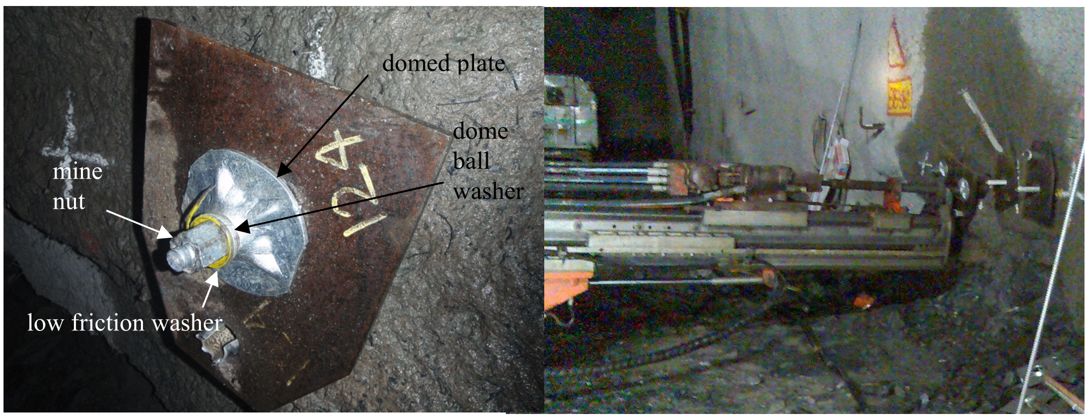


Figure 6. Surface hardware used on toe anchored resin bolts.

3 DYNAMIC TESTING RESULTS

Accelerometers, potentiometers, load cells, a high speed digital camera and rapid, time synchronized data acquisition software, ensured all displacements and accelerations were measured. By using known masses, forces can be calculated and compared with measured forces. Integration of force with displacement allows energy dissipation to be assessed for all components of the facility and at any time during the test.

The results are summarised in test report sheets that show the:

- energy dissipation by all system components,
- load-displacement curve at the simulated discontinuity,
- acceleration time curve of the loading mass,
- and the velocity time curve of the loading mass relative to the stiff beam.

A number of indices result to characterise the performance of reinforcement systems. These indices allow for comparison of different reinforcement systems. In particular it has been found that it is insufficient to only report dissipated energy. Other parameters such as total displacement, peak velocity and acceleration are required to assess performance.

The testing also shows the significant difference in performance by undertaking multiple loadings on a single reinforcement system to the failure point compared with a single load that fails the reinforcement system. Most importantly the energy dissipated from multiple small loads cannot be summed to conclude that the total will be the capacity for a single loading event. This is due to the change in bonding between the bar and encapsulation medium and that fracture toughness and sliding friction are velocity or strain rate dependent.

3.1 *Fully Bonded Threadbar – encapsulated in cement grout*

Typical force-displacement responses for fully encapsulated threadbar are shown in Figure 7. The responses include both steel yield and fracture of the bar at the simulated discontinuity. Table 4 summaries the results.

The encapsulated threadbar required plastic deformation of the steel bar at the simulated discontinuity to dissipate the input energy from the dynamic load. The dynamic axial loading and partial threads of the bar allow the grout to interlock and the shaft to break under some critical loading conditions. The critical loading conditions are related to the rate at which the energy is consumed in plastic deformation of the steel bar compared with the fracture growth between the steel bar and grout interface. At a sub-critical loading velocity the plastic deformation along the shaft of the bolt and the fracturing of the grout allow a free length to develop away from the simulated discontinuity towards the toe and collar of the bolt. The fracture process fills the partial threads on the bolt with a pulverised grout. This effectively reduces the embedment length towards the collar and the toe and increases the central length of the bolt over which deformation can occur.

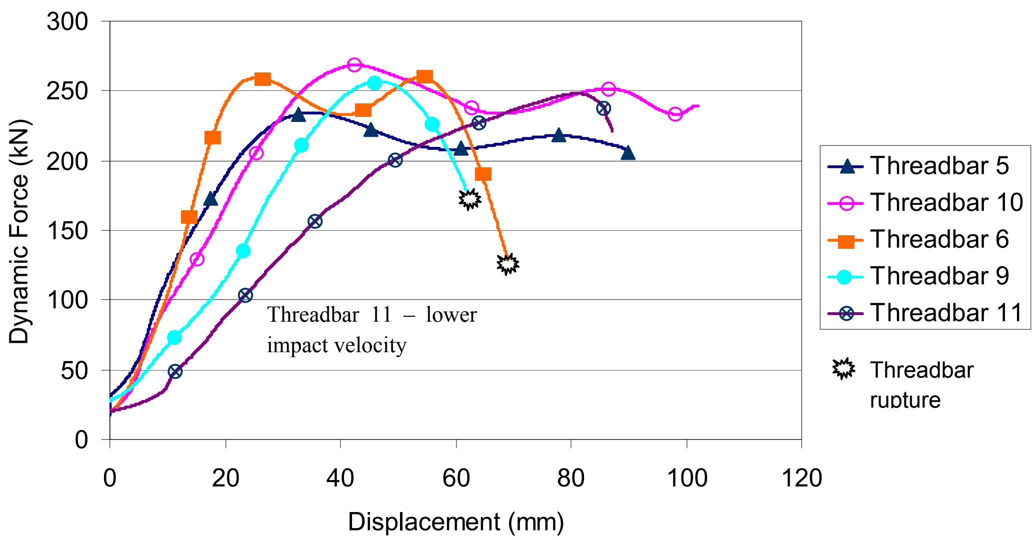


Figure 7. Dynamic force displacement curves at simulated discontinuity – fully encapsulated threadbar.

Table 4. Fully encapsulated threadbar summary results.

Bolt Number	Load Time (ms)	Displacement (mm)	Peak Deceleration (g)	Peak Force (kN)	Peak Ejection Velocity (m/s)	Energy Absorbed (kJ)	Results
11	56	92	-12	248	2.2	14.8	Bar streched
9	26	62	-12	256	3.0	10.9	Bar fractured at simulated discontinuity
6	28	69	-12	260	3.1	13.9	Bar fractured at simulated discontinuity
10	56	100	-13	270	3.2	20.8	Bar streched, no surface hardware
5	100	91	-13	235	2.4	17.5	Bar streched and pulled in grout, 5 year old grout

The difference in response to critical and non-critical loading of the fully encapsulated threadbar is clearly shown in Figure 8. In the first instance rupture of the bar occurred. In the other case plastic deformation of the bar is evident from the cracking of the galvanising.

Figure 9 shows that, when the subcritical loading occurs, the development of a debonded length changes the performance of reinforcement system. The bolt can then withstand loads that would have failed it when fully encapsulated.

Figure 8. Fully encapsulated threadbar – critical and non-critical loading conditions.

As the fracturing of the grout develops with successive tests, it then becomes possible for the threadbar to be pulled out of the grout. The photo clearly shows no damage to the grout away from the profile required to accommodate the threadbar and pulverised grout. This bolt was subjected to input energies of 25kJ, 36kJ then 49kJ which resulted in sliding of the bolt out of the grout.

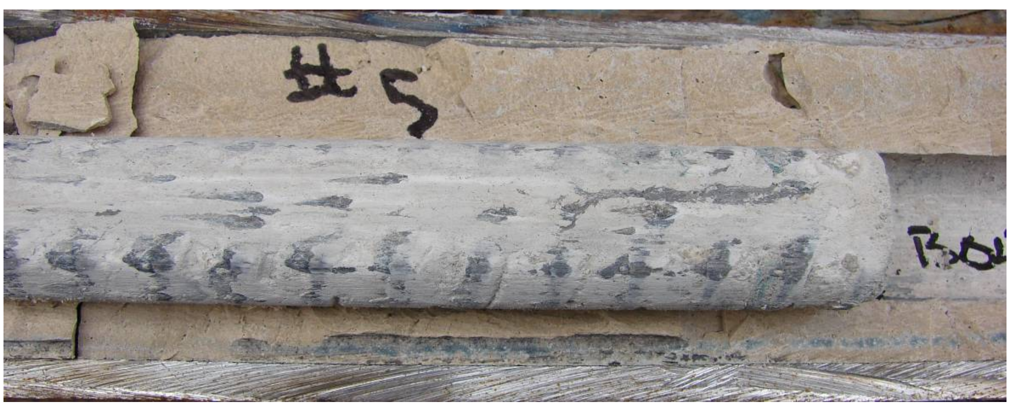


Figure 9. Threadbar that has slid out of the grout at the third dynamic axial load

3.2 *Partially Debonded Threadbar - encapsulated in cement grout*

The debonded threadbar required plastic deformation of the steel in the debonded length to absorb the input energy. To achieve this, the collar mass needed to transfer the load through the surface hardware and the side of the simulated bore hole onto the short length of encapsulated threadbar in the collar section. The dynamic force-displacement responses at the simulated discontinuity are shown in Figure 10. Figure 7 and 10 both show forces greater then the expected average static yield of 165kN. Malvar and Crawford (1998) have shown for strain rates approximating one strain per second there is a dynamic increase factor of approximately 1.3 in yield and ultimate strength capacities for reinforcing bar of nominal 550MPa yield stress. For 20mm threadbar this increases the average yield load from 165kN to 213kN.; a value that is in agreement with the dynamic yield load assessed in the facility.

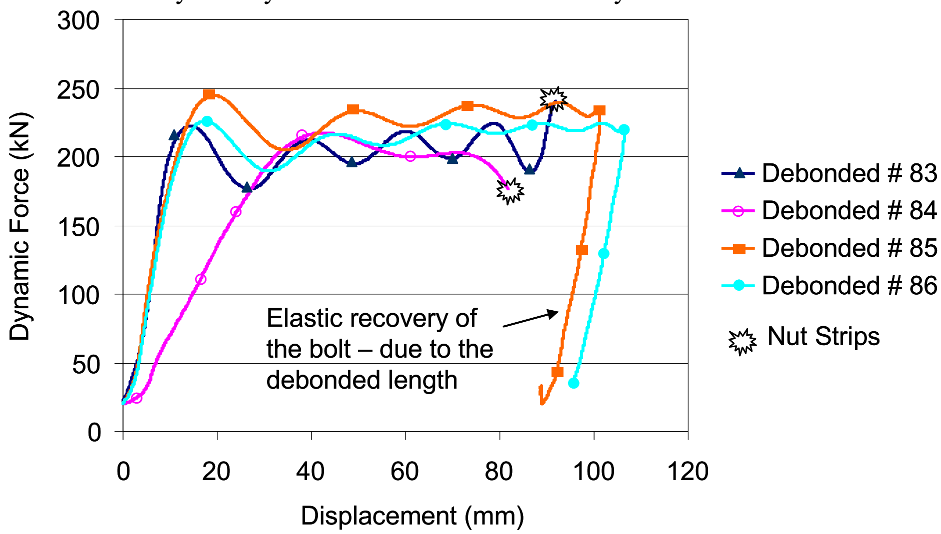


Figure 10. Calculated dynamic force displacement response for debonded threadbar at the discontinuity.

Table 5 summarises the test data for the debonded threadbar. The critical functionality for a debonded threadbar was the correct selection of the surface fixture. Testing with a mine nut and washer showed the mine nut would strip over the threads once 180kN was reached (as measured by a load cell at the collar), but when the longer integrated nut and washer was used this increased to 200kN. The failure mechanism changed to either survival of the surface hardware or partial shearing of the threads along the shaft of the bolt with the integrated nut, Figure 11. The second most important criterion appeared to be the collar length encapsulated by cement grout. Short lengths allow faster transfer of the load to the nut promoting failure before sufficient energy had been dissipated by yielding of the central debonded length.

Table 5. Debonded threadbar summary results.

Bolt Number	Load Time (ms)	Displacement (mm)	Peak Deceleration (g)	Peak Force (kN)	Peak Ejection Velocity (m/s)	Energy Absorbed (kJ)	Results
83	55	93	-11	240	2.5	18	Nut stripped
84	35	82	-10	217	2.6	13.6	Nut stripped
85	58	101	-12	244	2.6	21.8	Reinforcement system survived two drops
86	62	106	-11	226	2.6	21.6	Reinforcement system partial thread shearing on second drop.

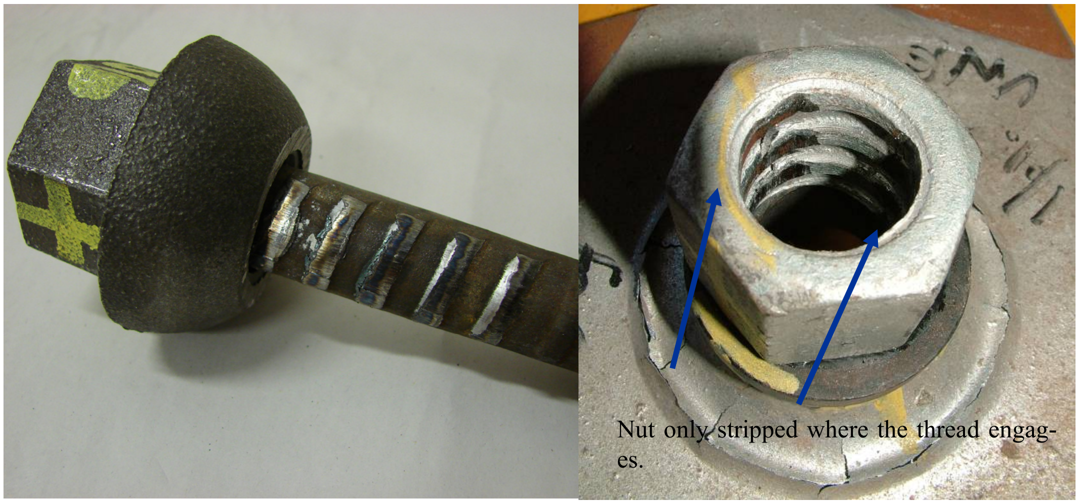


Figure 11. Shearing of the thread on the bar and mine nut.

3.3 *Resin Encapsulated Threadbar Installed by Jumbo - toe anchored*

The toe anchored bolts had no encapsulation medium within the collar section of the reinforcement system, i.e. collar side of the simulated discontinuity. This meant that in a dynamic test the collar load was applied directly onto the domed plate and then through the nut onto the thread and then along the shaft of the bolt.

All bolts failed by early stripping of the nut and thread off the bolt. Table 6 summaries the results of the test program. Bolt 124 also had the same result of nut and thread stripping, but sensor saturation made a solution difficult. Two of the stripped nuts and threads are shown in Figure 12. No difference in performance was noted for either the jumbo tensioned or hand tensioned bolts.

The short load duration leading up to failure of the bolt made analysis quite difficult. The capacity of the nut in response to dynamic loading is a major deficiency of the system. A reinforcement system that has no load distribution capability from the rock to the reinforcing element between the end of the encapsulation medium and the surface hardware must have a fixture at the collar that can transfer load for a considerable period. The mine nut test does not achieve this requirement.

The results show that very low energy absorption will result when a full encapsulation is not achieved for this reinforcement system.

Table 6. Summary of resin encapsulated toe anchored bolts

Bolt Number	Input Energy (kJ)	Load Time (ms)	Displacement (mm)	Peak Deceleration (g)	Peak Force (kN)	Peak Ejection Velocity (m/s)	Energy Absorbed (kJ)	Results
125	12.6	7	15	-26	196	2.2	0.9	Nut and thread stripped
126	36	6	12	-8	159	1.7	1.1	Nut and thread stripped
127	21.7	6	8	-8	155	1.5	0.8	Nut and thread stripped

Figure 12. Thread stripping on the nut and bar.

3.4 *Summary Results*

The results from the tests on the three systems are summarised in Figures 13, 14 and 15. The results shown are for the standard WASM dynamic test of 36kJ input energy. Any special conditions are noted. All data points are from the first loading of the reinforcement system and a circled data point indicates failure (i.e. critical loading conditions). Although the 20mm threadbar is not considered to be generally applicable to a dynamic loading situation, reasonable performance could be obtained with the use of the central debonding and an increased embedment length at the collar to delay or reduce load transfer to the nut, along with an integrated nut and washer.

The results have been compared with two dynamically capable reinforcement systems; the 22mm diameter cone bolt in 40MPa grout from South Africa and the Garford Yielding Bolt from Australia. A key feature of both of these bolts is a yielding mechanism and high nut thread capacity. Specifically designed dynamically capable reinforcement systems should be used where stress driven damage to excavations is expected.

Although no published data has been found on changes to the fracture toughness of aged grout (>5yrs old) the test data (summary graphs) do indicate an effect whereby the grout is fractured more easily and allows a generation of debonding rather than failure of the shaft of the bolt at the simulated discontinuity.

Figure 13 shows increasing energy dissipated with increasing separation at the discontinuity, in part due to the additional change in potential energy from the displacement of the loading mass. The testing also suggests a lower bound to which the reinforcement system must be capable of deforming to dissipate the energy; anything less will result in system failure. A similar effect is noted in Figure 14, where a minimum time required to dissipate the energy to ensure system survival is suggested. Figure 15 shows how increased displacements occur with lower average resistive forces in response to the same loading energy.

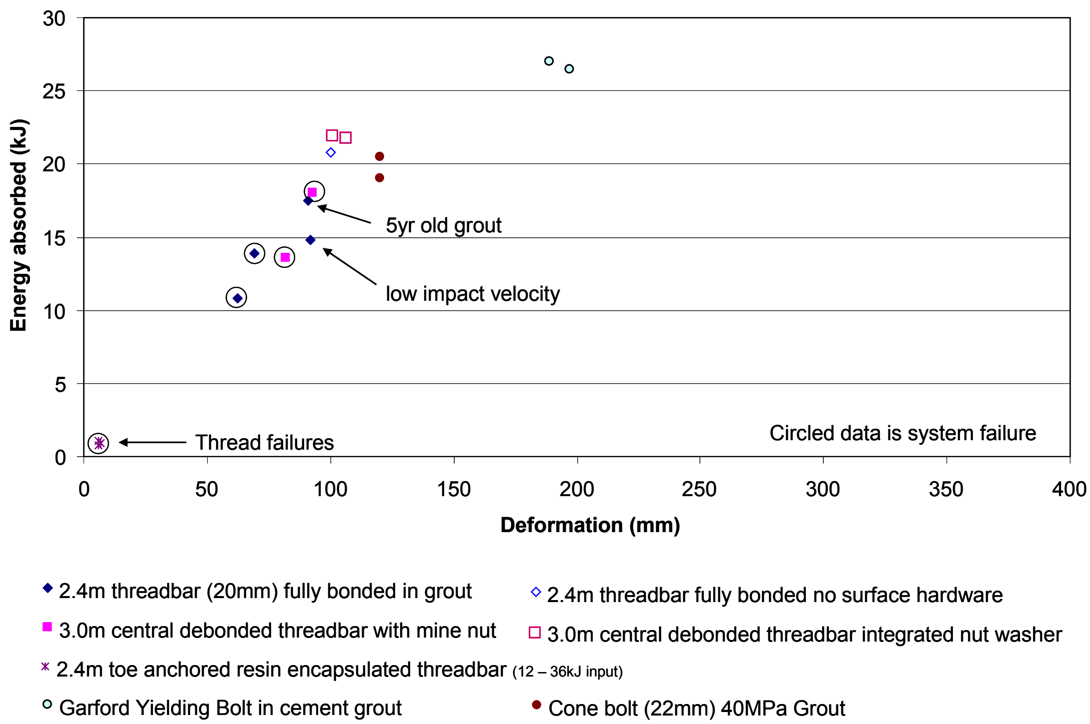


Figure 13. Energy dissipated by reinforcement system against displacement at discontinuity.

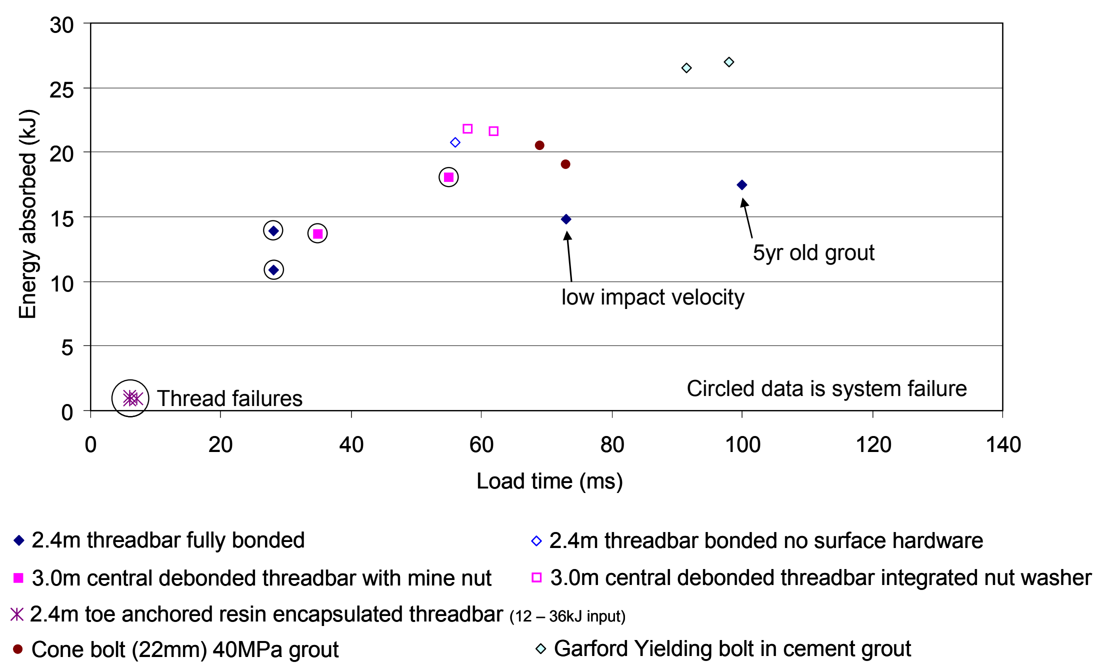


Figure 14. Energy dissipated by reinforcement systems and loading time.

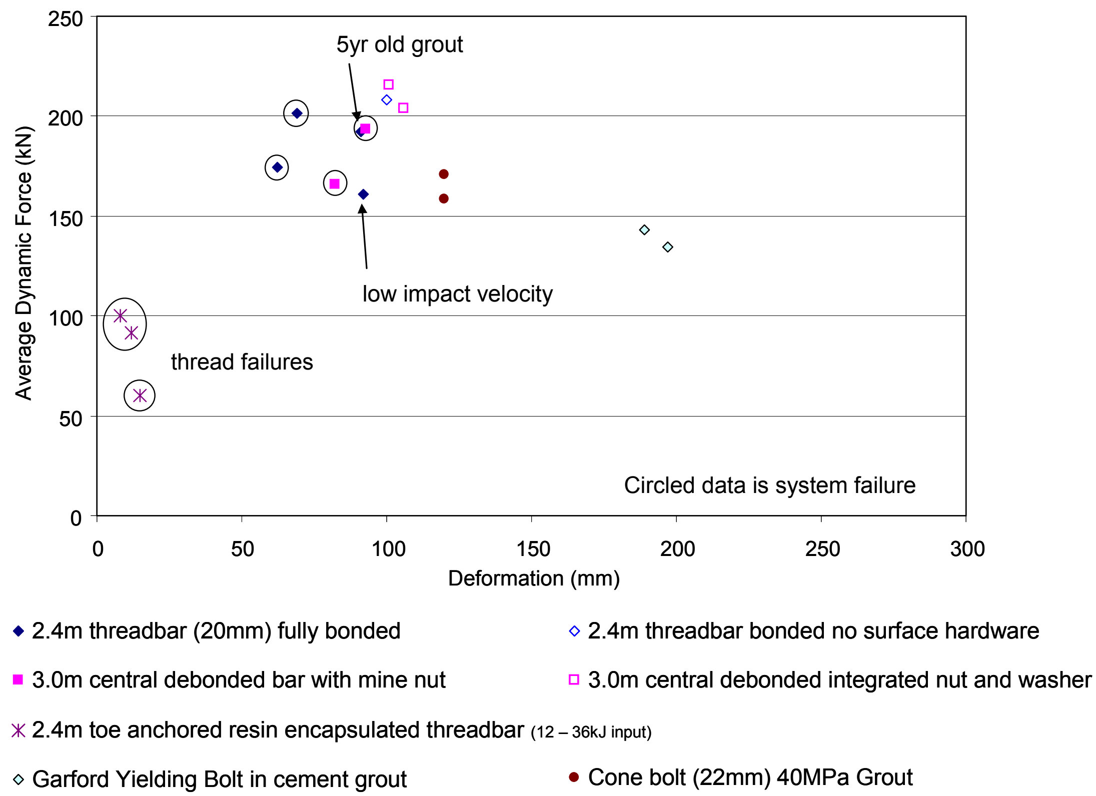


Figure 15. Average dynamic force and deformation from WASM dynamic testing.

4 CONCLUSIONS

A comprehensive double embedment length dynamic test program has been undertaken on 20mm diameter threadbar.

WASM testing has shown that for high strain rates the work by Malvar and Crawford (1998) on the dynamic increase factors the strength of steel reinforcing bars is applicable. The program identified that, for all geometries tested, the type of encapsulation medium, toe and collar embedment lengths, surface hardware and loading conditions all can be critical to the performance of the complete reinforcement system.

The testing program identified a significant change in capacity and performance between loading threadbar with sufficient energy to fail the reinforcement system on the first load, i.e. critical loading, compared with, the repetitive loading of the reinforcement system at a lower energy which does not fail the bolt, but rather progressively plastically deforms the bar. The loading at a subcritical strain rate that does not snap the bar results in yielding of the bar and the generation of a debonded length about the simulated discontinuity; for fully encapsulated bolts this changes the configuration and performance of the reinforcement system in response to the next loading.

The mine nut does not have sufficient thread engagement and would also appear to be able to expand radially under dynamic loading; this reduces thread contact to further promote shearing of the partially engaged threads. This is less likely to occur with the integrated nut due the increased steel volume and increased radial resistance to expansion.

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REFERNCES

Hyett, A, Bawden, WF & Reichardt, R 1992, 'The Effect of Rockmass Confinement on the Bond Strength of Fully Grouted Cable Bolts', *Int. J. Rock Mech. Min. Sc.& Geomech. Abstr,* vol. 29, no. 5, pp. 503-524.

Malvar, LJ & Crawford, JE 1998, 'Dynamic increase factors for steel reinforcing bars', in *28th Department of Defence Explosive Safety Board Seminar,* , Orlando, Florida, August 1998.

Player, JR, Villaescusa, E & Thompson, AG 2004, 'Dynamic testing of rock reinforcement using the momentum transfer concept', *Proceedings of the Fifth International Symposium on Ground Support*, eds. E Villaescusa & E Potvin, Balkema, Perth, pp. 327-340.

Player, J, Villaescusa, E & Thompson, AG 2008, 'An Examination of Dynamic Test Facilities', *Australian Mining Technology Conference*., CRC Mining, AusIMM, pp349-379.

Wood, S.L, 1992. 'Evaluation of the Long-Term Properties of Concrete', *Portland Concrete Association* – Research and Development Bulletin RD102T, 101pages.

Yeomans, SR. 2004. Galvanised Steel Reinforcement in Concrete. Elsevier, 297pages.