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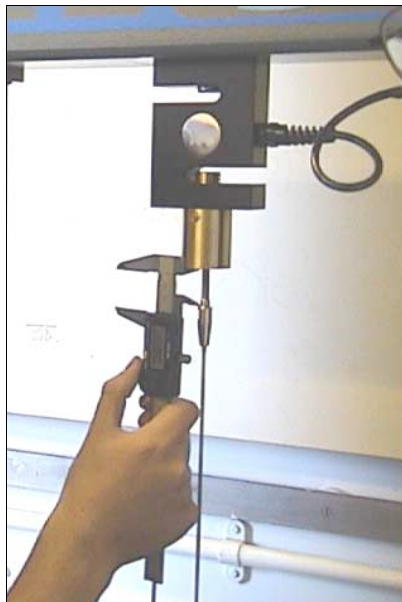
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PhD Project
**Design And Analysis Of Innovative Wire /
Rod Networks**

Investigation on the Failure of
3mm Compression Terminations

Kevin Bell and Gareth B. Neighbour



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EXECUTIVE SUMMARY

This report gives the findings of a number of tensile experiments carried out on Hi-MOD 3mm compression stud fittings. The report describes the experimental method that was used and presents the data collected. The report also contains details of design modifications based on data from the first set of tests and an analysis of whether or not the modifications were successful. In short the following conclusions were made:

- It was shown that the ability of the compression fitting to distribute loads evenly in a cable has a major impact on its performance.
- It was shown that a single slot in the cone of a compression fitting is insufficient to achieve acceptable performance.
- In comparison of the swage fittings to the compression fittings, it was observed that the swage fittings had a far greater element of slip associated with pullout of the cable from the swage. However, in other respects, the load-deflection curves were similar.

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1. Introduction

Compression fittings are becoming an increasingly adopted method of terminating a wire (as opposed to swage fittings) due to the possibility of affecting a wire termination without the requirement for any specialist tooling. It is essential therefore that as much as possible is understood about the functionality and through-life performance of these fittings.

This report describes the results of two sets of tests carried out on three millimetre compression fittings between 3rd September 2002 and 28th May 2003. The first series of tests undertaken compare the fittings with tests done on the same cable but a different termination method and with tests undertaken on a larger size of compression fitting. The second series of tests investigate improvements to the design of the compression fitting identified from the first series of results.

2. Compression Fittings

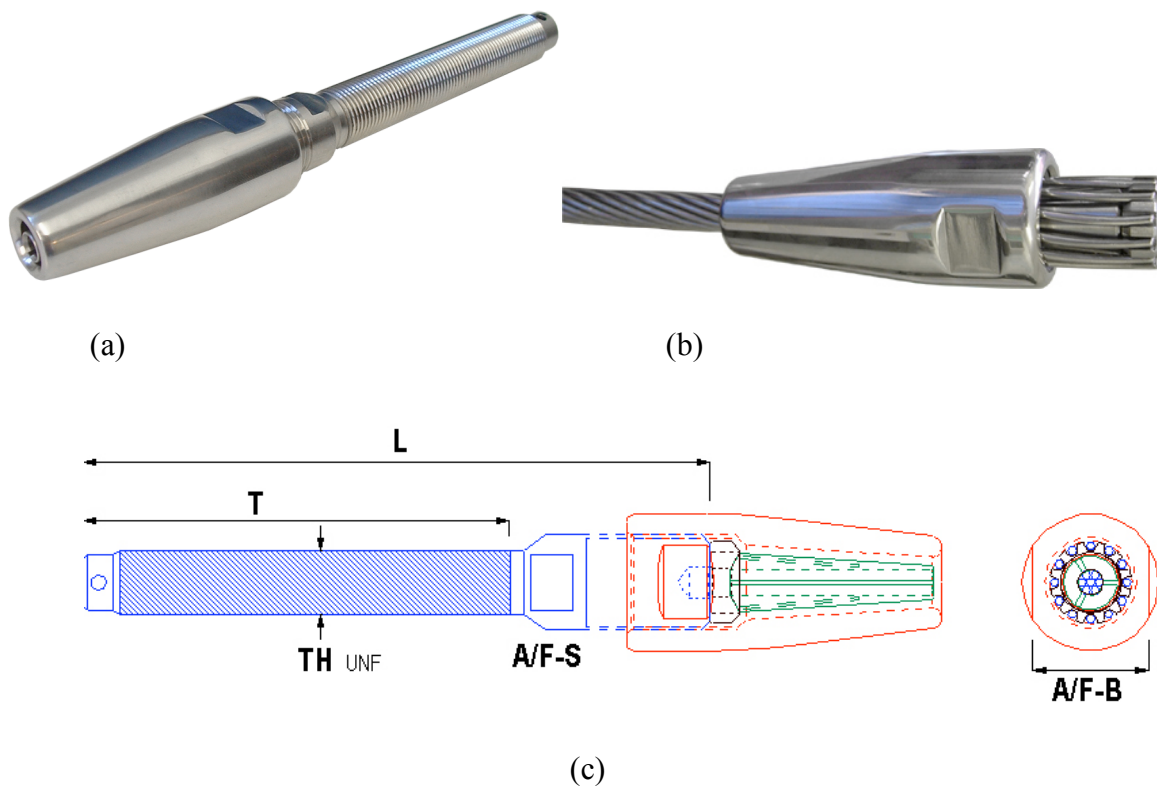


FIGURE 1: Hi-MOD Compression Fitting. (a) Compression stud fitting for steel cable. (b) Detail of an assembled compression fitting (note the even spacing of the outer strands facilitated by the special star shaped crown ring - a key feature of this particular make of compression fitting). (c) Line drawing section view of a compression fitting, the wedge shaped cone (shown in green) grips the wires as they are put in tension preventing the cable from pulling out.

A compression fitting consists of a wedge shaped collet (cone) inside a conical body that is internally tapered to accommodate the cone (see Figure 4(c)). The fitting is assembled by passing the body over the end of the cable, opening up the outer strands and placing the cone over the core of the cable. The outer wires are then closed back up around the cone with the crown ring ensuring that the wires are evenly spaced so as to avoid unbalanced loads. The body is then pulled over the assembly and the end piece screwed to main body and tightened to ensure rigidity. It perhaps should be noted here that the clamping force due to the wedge motion of a compression fitting can be estimated using the principle of “Conservation of Work”. The inclusive angle of the slope for a Hi-MOD compression fitting is 8° which corresponds to every 7mm the cone moves in, it must compress the internal fittings by 1mm. This implies that for every unit of tensile force in the cable there is a corresponding total compressive force due to the wedge of seven units of force.

3. The Testing Machine

The testing was carried out on a Lloyd Instruments EZ50 testing machine connected to a PC running Lloyd’s NEXYGEN MT data logging and analysis software. The first set of tests was performed using Version 4.0 of the NEXYGEN MT software and the second set using version 4.5. The machine was of a twin-column, twin-lead screw type and incorporated a crosshead guidance system that prevented side loading of the test pieces. Extension and load data was logged on a PC connected via an RS232 interface to the testing machine with a data sample rate of 8 kHz. Extension resolution was better than $0.1\mu\text{m}$. A Lloyds XLC-50K-A1 50kN load cell with a 1.0 N resolution mounted in the crosshead was used to capture the load data.



FIGURE 2: Lloyd EZ50 testing machine

4. Description of Tests

The NEXYGEN MT software was set up to perform a “Pull to Break” test (NEXYGEN ref. # 40/0640). The tests were performed with no preload, slack being taken up manually and the machine then being zeroed at that point. The crosshead speed was varied between 1 and 8 mm/minute for the first set of tests¹. No correlation was found between the crosshead speed and the maximum load or deflection at maximum load for this range of crosshead speeds (see Bell *et al.*, March 2003). Consequently, the second test series were performed at a crosshead speed of 4 mm/min. Each test was terminated at rupture with a rupture being defined as a drop in load to 20% of the maximum value. The rupture detection became active at 2 kN.

The test pieces comprised a length of cable with an identical termination at each end. The total length of cable was 300 mm with a free (outside the terminal) length of approximately 265 mm.

¹ The reason for this was to establish any failure load dependency upon strain rate.

After various dimensional measurements had been taken, the test piece was secured in the EZ50 machine by two aluminium-bronze bushings - one directly into the base of the machine and the other into the 50 kN load cell.

5. Experimental Observations: CTS03 Compression Stud for 3mm 1x19 Cable

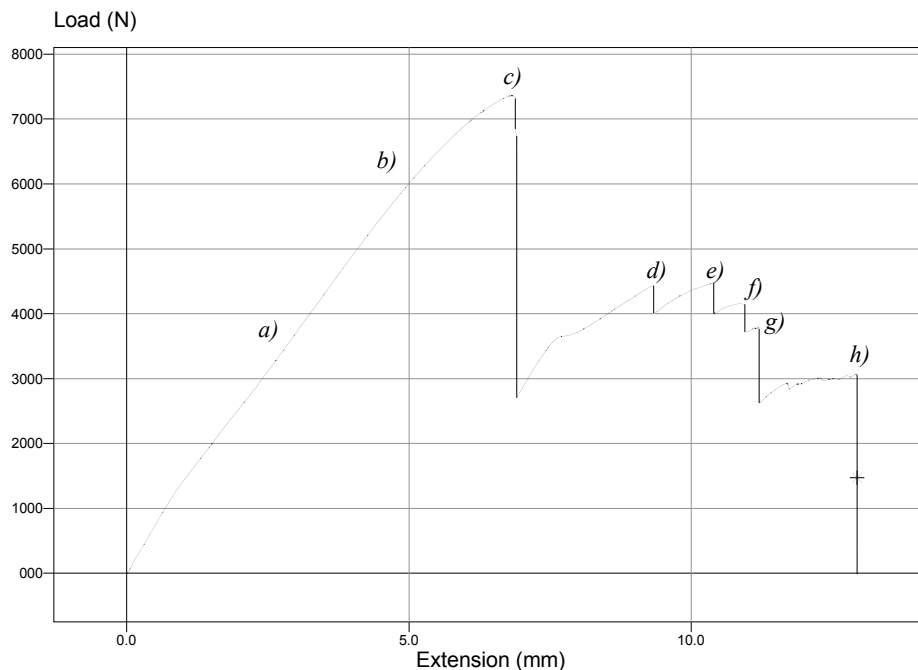


FIGURE 3: Typical Load / Extension curve for CTS03 sample.

Figure 3 shows the load / extension for the first of the CTS03s to be tested. Although every test produced slightly different results, they all (both the first and second batch of samples) demonstrated the same basic behaviour, *i.e.*

- a) Initial 'straight line' behaviour.
- b) Curve enters what would classically be the plastic phase.
- c) Seven outer strands broke at the top fitting.
- d) One outer strand broke at the bottom.
- e) One outer strand broke at the top.
- f) One outer strand broke at the bottom.
- g) Three outer strands broke at the bottom.
- h) Large-scale central core pull out at bottom – test terminated.

In this particular, the experimental load-displacement trace indicated by the small drop in load that there were 13 occurrences of an outer wire breaking. This, initially, seems at odds with the construction of the cable-termination system since there are only twelve outer wires. However, further investigation showed that one particular wire broke first at one end and then later in the test, broke at the other end. This observation reveals the remnant strength that is retained in such a system by the interaction between the various wires in cable.

6. Analysis: CTS03 - Compression Stud for 1x19 Wire: Batch I 03-10-02

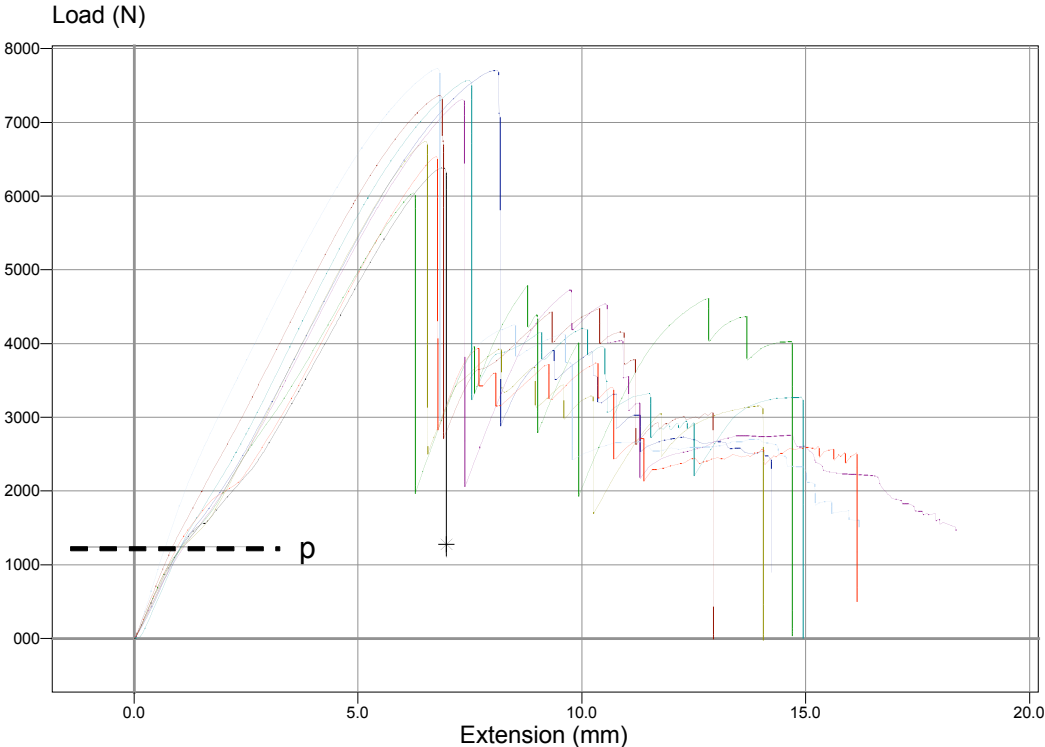


FIGURE 4: The load / extension curves for nine different CTS03 assembly samples tested on 03/10/02

All the samples displayed similar behaviour to one another. However, unlike the swage fittings tested at the same time (Bell *et al.*, March 2003), the compression fittings exhibited greater variability in the initial ‘straight line’ portion of the graph. It is most likely that the variability arose as a direct result of the way in which the gripping force is generated for the two styles of termination. During assembly the swage fitting is clamped onto the wire by means of a press or cam shaped clamping dies and so grips the wire firmly even if no tension is present in the wire. The swage fitting requires a tension in the wire to provide the necessary force for the wedge action to grip the wire. By the very nature of how it works the wedge action requires the wire and collet to move into a smaller space than it would normally occupy under zero load and this movement is considered the most likely reason for the difference in the two load-displacement response between swage and compression fittings.

It can be seen in Figure 4 that a change of gradient occurs at the point *p*. In all cases this gradient change is to a lesser slope, the gradient then subsequently increases this suggests that a certain amount of slippage is occurring at this point. The fitting is designed with sufficient thread length internally to allow the end piece to push the collet and wire into the body establishing an initial grip to prevent the wire falling out during installation. It is thought that the gradient change is due to this small amount of pre-tensioning done when the fitting is tightened during assembly. Once the load exceeds that which can be held by this amount of initial grip, the fitting slips slightly and then re-grips. In all cases the fittings were tightened using a spanner with the component held in a vice. A torque wrench was not used so there is no guarantee that the fittings were tightened by the same amount however they were all assembled by the same person and intuitively tightened to roughly the same degree. The fact that the gradient change for all the samples occurs at approximately the same load demonstrates that the amount of pre-tensioning was fairly uniform.

To estimate the degree to which slippage was causing the variations in the load extension curves the stiffness was calculated for each test in two ways. Firstly a tangent was drawn to the curve at the point of greatest slope on the stress-strain curve and the gradient was taken, the tangential modulus. Secondly the secant modulus was calculated by drawing a line between the origin of the load-percentage strain curve and the maximum load.

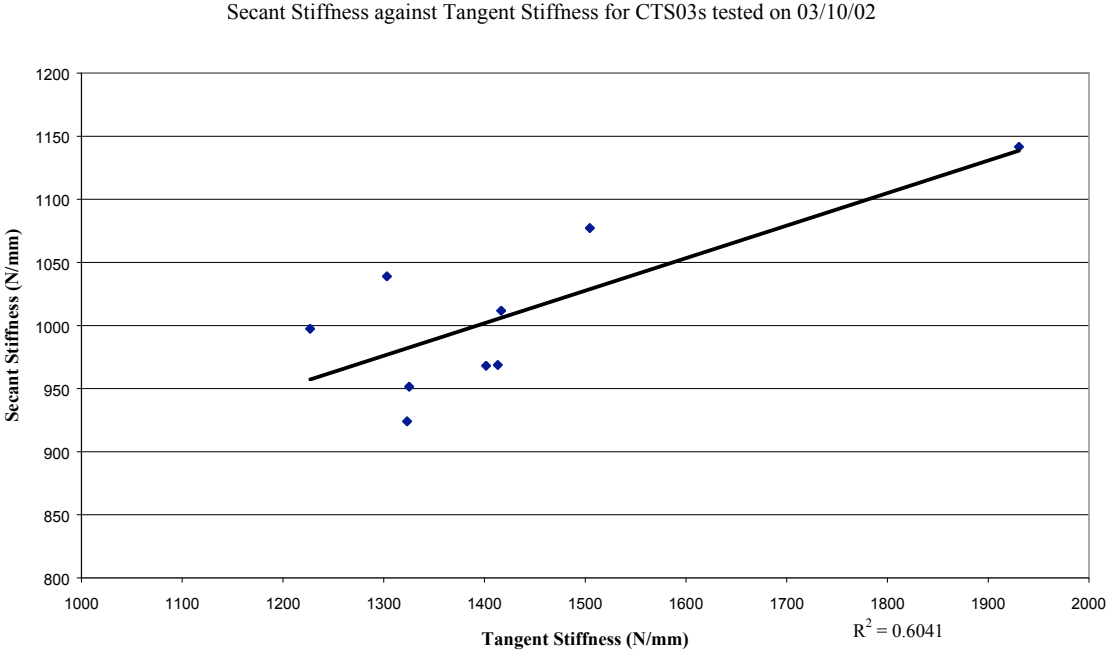


FIGURE 5: Secant stiffness against Tangent stiffness for CTS03s tested on 03/10/02

Classical linear-elastic behaviour would result in the secant and tangential stiffness being the same. The swaged assemblies demonstrated elasto-plastic behaviour, which is typical of stainless steels. Clearly one would expect that the wire would behave in the same way regardless of how it was terminated if the termination was holding the fitting firmly. The swageless assemblies showed a great deal more inconsistency, which suggests that there was some slippage of the wire occurring as the assembly was being tested. This is consistent with observations both during testing and from inspection of the graphs (Figure 4; point *p*).

The average peak load for the CTS03s was 7045.36 N with a deviation of 592.24 N; contrast this with the SC1/4x3s, which had an average breaking load of 8250.61 N and a standard deviation of 56.66 N. Clearly, the compression fitting was holding the cable in such a way that the full breaking load of the whole cable was not being achieved. Conceptually, the design intent is for the compression fitting to perform by reliance on the collet closing onto the central core thereby restricting any movement. Furthermore, the design intent is such that the weakest part of the system is the cable itself, i.e. the compression fittings should not inhibit the cable taking the maximum load. If the collet does not close onto the core properly then clearly the outer strands will take a disproportionately high fraction of the load causing the cable to fail below its true breaking load. On inspection after testing, it was apparent that the central core of the 3mm cable had pulled through the collet by considerably more than the outer strands.

An important concept to introduce at this point is the *wire recovery length* (Raof and Kraincanic, 1998), which is defined as the length from point of fracture that a wire takes up its proportion of the full load due to radial pressure from the helix and interwire friction. Raof and Kraincanic suggest a model for calculating the wire recovery length and they were able to show the model

agreed well with experiment. However for the purposes of understanding the fittings it is unnecessary to know what the wire recovery length is only that such a thing exists.

This concept is important as it means that end effects due to the termination diminish as a function of distance from the cable end. The implication of this result is that if the termination produces any unbalanced loads in terms of the direction or distribution between the core and the outer wires then the length of outer wire between the point of emergence from the fitting and the point where contact with the core is re-established is where a break is most likely to occur, as this is where the load will be at maximum. Considering the fact that the central core appeared not to be taking its full share of the load as evidenced by the disproportionately large degree of pullout of the central core it was unsurprising that in all cases the outer wires broke first in this area.

On inspection it became apparent that the failure of each wire had occurred in the same way and always at the same location with respect to the compression fitting; this required extra explanation. Fracture propagated from the point where the wire contacted the end of the cone and then spread back along the wire at an angle of 45° to the direction of loading. It was concluded that the point deformation due to the edge was weakening the wires and hence causing this fracture mechanism. Actually, there were two mechanisms occurring simultaneously which were causing the compression fitting assemblies to fail in such a manner outlined above. Firstly, the uneven load distribution between the wires due to the central core not being gripped correctly and secondly, the deformation of the wire due to the cone edge. It was important to try and reduce one of these effects in order to gain a clearer picture of what was happening.

7. Design Modifications

The inconsistent behaviour and weakening of the cable were not the only issues with the 3mm fitting. They were found to be excessively difficult to assemble onto the cable; the outer wires would not sit properly around the cone, the wire had a tendency to ‘bird cage’ just outside the fitting and the crown-ring was prone to sit at an angle spilling the wires out of the pockets. An analysis was undertaken to obtain the ratios of various dimensions to the wire diameter for all sizes of compression cone to see why the 3mm fittings were more difficult to assemble than any other size. It was found that the cone of the 3mm fitting was approximately 25% longer than the typical fitting and thus requiring the first design modification to reduce the dimension in line with the compression fitting family of parts. The second design modification related to the diameter of the hole in the centre of the crown ring; this was reduced to prevent it from sitting at an angle and at the same time, the depth of the pockets was increased. These changes made the fittings much easier to assemble. The third design modification related to the size of the hole at the end of the body; this was found to be larger than was typical for this range of parts and consequently was reduced to eliminate the problem of the ‘bird caging’.

For comparison of performance, similar tests were also undertaken on 6mm compression fittings (Bell *et al.*, March 2003), which were previously found to be more typical of the range (the typicality being established by the analysis of ratios). The 6mm fittings performed very well both in terms of ultimate breaking load and consistency of behaviour with respect to the failure mechanism. The primary difference between the 3mm and the 6mm fittings (and indeed the whole range) was that the cone in the 3mm fittings only had one slot. Since the inconsistent performance was judged to have been due to the core not being gripped correctly the most obvious change to make to try and improve the performance was to put two slots in the 3mm cone (the fourth design modification). Once these design changes had been approved and introduced a second series of tests were undertaken to evaluate their performance.

8. Analysis: CTS03: Compression Stud For 1x19 Wire: Batch II 28-05-03

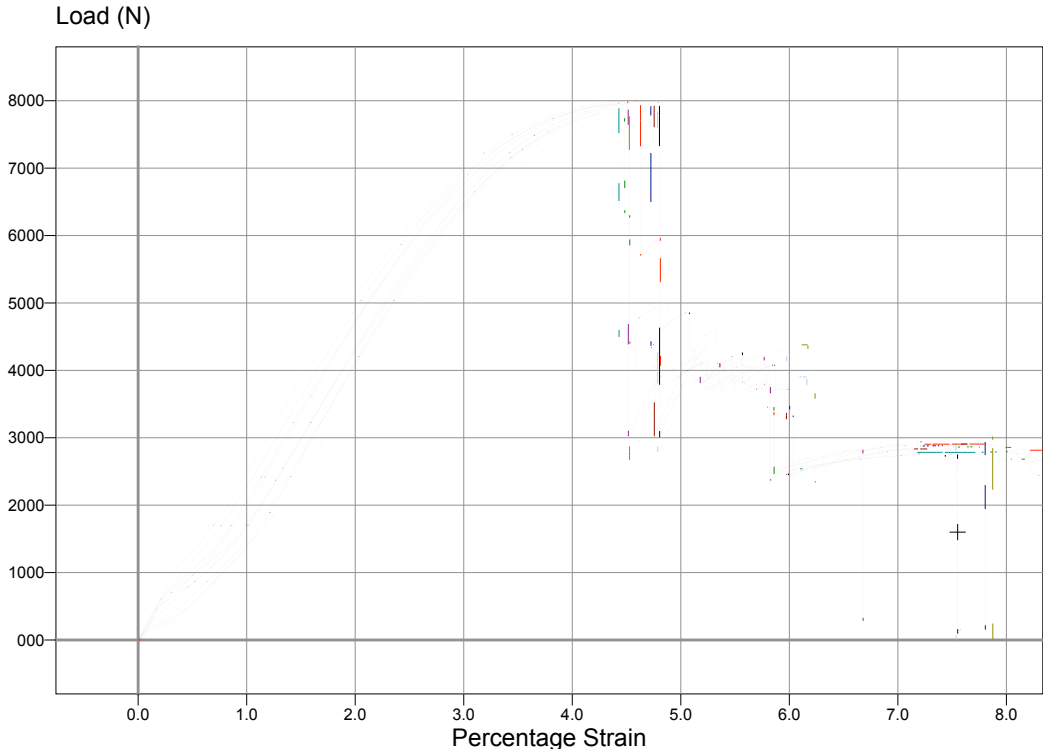


FIGURE 6: The load / percentage strain curves for nine different CTS03 assembly samples tested on 28/05/03

Figure 6 shows the load against percentage strain curves for the re-designed 3mm compression fittings. The most striking characteristic of this figure is the consistency of the data. The mean breaking load was 7955 N with a standard deviation of 62.2 N.

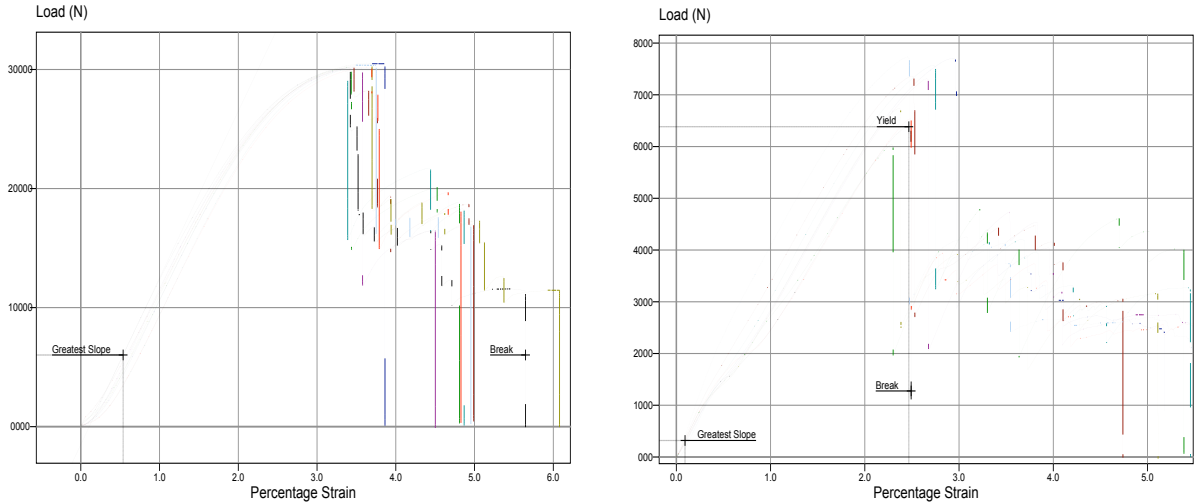


FIGURE 7: The load / percentage strain curves for CTS06s tested 11/12/02 (left) and CTS03s tested 03/10/02 (right)

Comparing Figure 6 with the graphs in Figure 7, it is clear that the re-designed 3mm compression fittings have improved considerably in consistency of performance to a level comparable to that of the 6mm compression fittings (Bell et al., 2003).

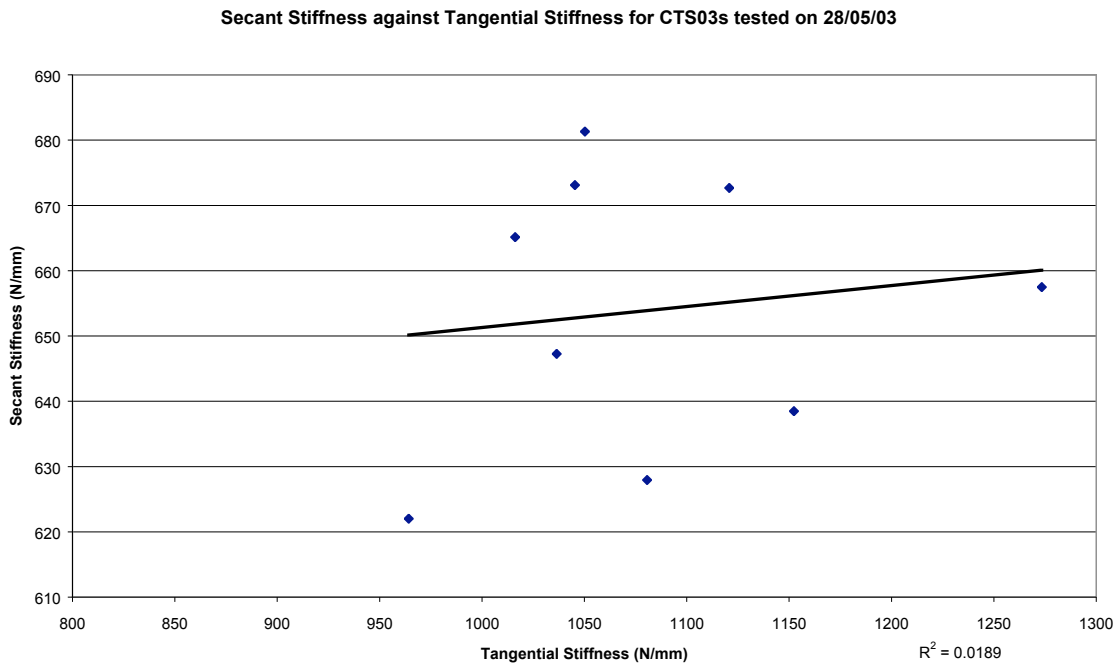


FIGURE 8: Secant stiffness against tangent stiffness for CTS03s tested on 28/05/03

Despite the consistency of the data there appeared to be no correlation between the secant and tangent stiffness (Figure 8). Referring back to Figure 6, the load / percentage strain curves for all the fittings tested on 28/05/03 initially started out at the same very sharp gradient and then deviate from this at different points. The initial sharp gradient is likely to have been due to ‘pre-compression’ as a result of the tightening of the end fitting into the body (pushing on the crown ring and the cone). It could have been the case that the lack of correlation was due to this pre-compression and so the tangent stiffness was measured at a point past the initial gradient at the next point of greatest slope.

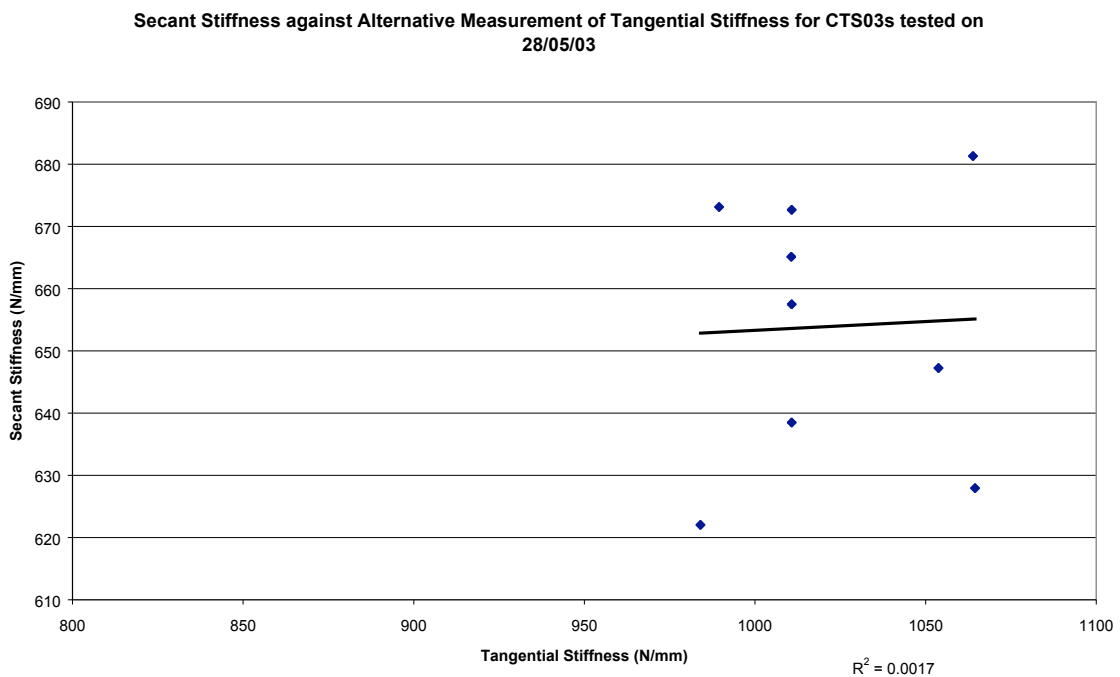


FIGURE 9: Secant stiffness against alternative measurement of tangential stiffness for CTS03s tested on 28/05/03

Figure 9 suggests that there is still no correlation between the secant and tangent stiffness regardless of having measured the tangent stiffness at a point sufficiently far from the start of the load / extension curve to be able to ignore any effect that the preparation of the test samples may have had on the results. One feature of Figure 9 that is quite striking is the consistency of the tangent stiffness which when measured at that point gave a mean tangent stiffness of 1022 N/mm with a standard deviation of 31. The low standard deviation reinforces the assertion that the performance of the re-designed fittings is very consistent.

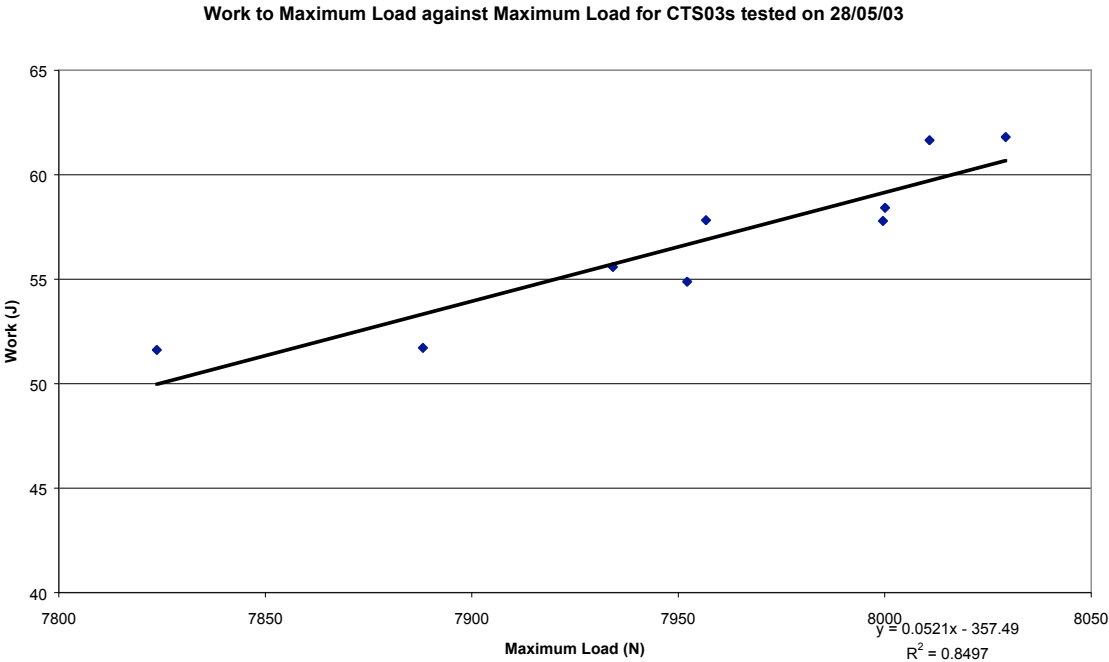


FIGURE 10: Work to maximum load against maximum load for CTS03s tested on 28/05/03

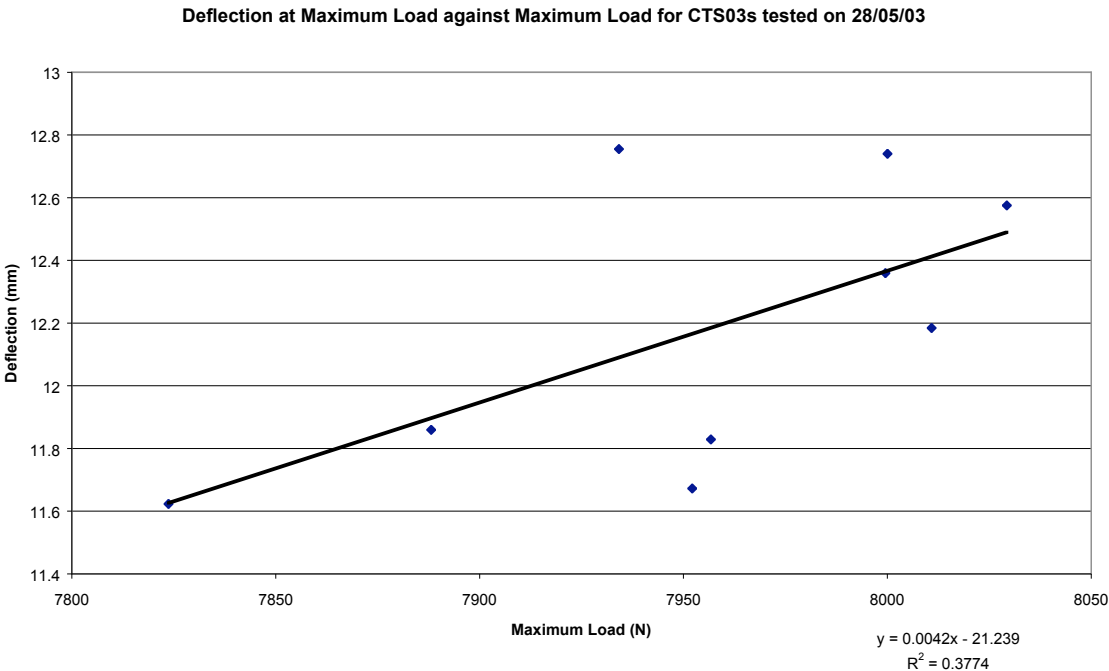


FIGURE 11: Deflection at maximum load against maximum load for CTS03s tested on 28/05/03

Since work done is a product of distance and force, one would naturally expect a good correlation in both Figures 10 and 11. However there would appear to be no correlation between the

deflection and the work. This suggests that there is some noise in the initial portion of the load / extension curves (most likely due to the pre-compression); this would also explain why there is no correlation between the secant and tangent stiffness (although the secant stiffness data for the re-designed fittings was much more consistent than for the original design of fittings). It should be possible to reduce the effects of the noise by obtaining more data points.

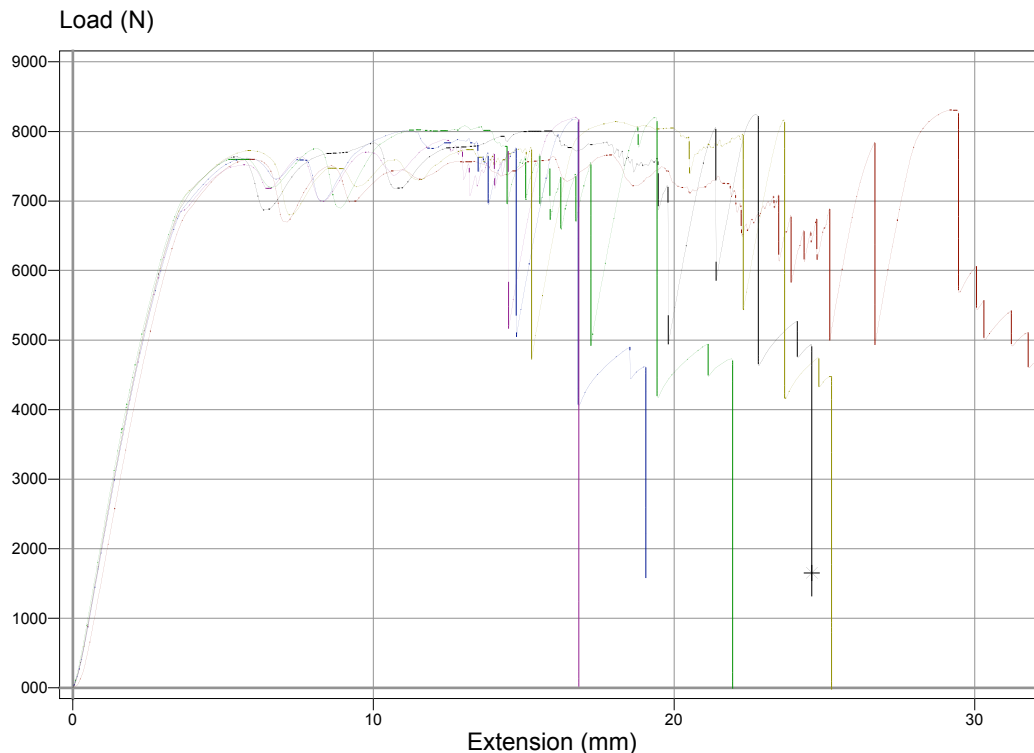


FIGURE 12: Load extension curves for 3mm swage terminations tested on 10/03/02 (Bell *et al.*, March 2003)

Figure 6 shows that although the swage fittings achieved a higher breaking load than the compression fittings they only did so after a large degree of pullout had occurred. In all cases tested the pull out was arrested by cold welding and the wire broke, however, this process was found to be highly unpredictable as is evidenced by the rightmost curve. In service, therefore, it would be unwise to use the swage fittings at load higher than about 7.4 kN. In contrast, Figure 6 shows that the compression fittings behave in a predictable and repeatable manner right up to the breaking load of 8.0 kN, outperforming their equivalent swage fittings.

As was undertaken for the 6mm compression fittings, the “official” breaking load for the wire tested was obtained from the manufacturer, Kos Tech. The figure for the (tested) breaking load was 7409 N, nine standard deviations below the mean value obtained in these tests of 7955 N. The difference between the two load values is not attributed to material differences in the batch, but due to mechanical testing techniques.

A *t-test* was performed to establish whether the first and second data sets could be considered to be part of the same statistical population.

- A value of *t* of 2.12 was obtained from a set of statistical tables for a *two-tailed t-distribution* at the 95% confidence level.
- A null hypothesis was established that if the calculated *t* was less than the value from the tables then both sets of data belonged to the same distribution.

- An alternative hypothesis was established that if the calculated t was greater than the value from the tables then the data sets belonged to different distributions.

	03/10/02	(x-mean)^2	28/05/03	(x-mean)^2
	7367.027	103469.8733	8029.3	5523.792716
	6045.345	1000029.334	7823.7	17233.85494
	6742.587	91671.28768	7888.2	4459.271605
	7710.157	441955.4944	7999.5	1982.228272
	7310.863	70492.02001	7956.7	2.966049383
	7573.252	278670.3156	7952.2	7.716049383
	7735.767	476662.2859	7934.2	431.7160494
	6539.955	255433.8771	8010.9	3127.294938
	6383.284	438344.1884	8000.1	2036.014938
Mean	7045.3597		7954.978	
Variance		394591.0845		4350.606944
$S^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$		=	199470.8	
		S =	446.6216	
$Calc\ t = \frac{\bar{x}_1 - \bar{x}_2}{S \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$		=	4.320417	

FIGURE 13: t – test to compare the distributions of CTS03s tested on 3/10/02 and 28/5/03

The calculated value of t was found to be greater than that from the tables and so the null hypothesis was rejected and the alternative accepted. The implication of this result is that the design changes have significantly increased the load (at 95% confidence level) at which the wire-termination system fails (for the CTS03 assemblies).

In all cases the outer strands broke before the core wire, however there is nothing to suggest that this is due to an uneven load distribution. On inspection of the fittings after failure it was apparent that failure propagated back at an angle of 45° from the front outside edge of the cone as with all the other tests performed. It is apparent that reducing the stress where the outer strands are in contact with the forward outer edge of the cone could bring about further improvements to the efficiency of the fittings.

9. Summary and Conclusions

The original design for a 3mm compression fitting was tested. Analysis of the test results showed that the fittings were performing at a lower level than expected compared to preliminary tests undertaken for other sizes of compression fittings. It was concluded that this was due primarily to insufficient grip on the central core. It was also found that assembly of the 3mm fittings was much more difficult to assemble than for any other size. An analysis was carried out to identify the design features that were responsible for these differences.

It was found that the equivalent 6mm compression fittings were much more typical of the range and so these were tested to obtain a benchmark performance. The 6mm fittings performed very well (Bell *et al.*, March 2003) and a decision was made to re-design the 3mm fittings in-line with geometry adopted for the 6mm fittings; the primary differences being the size of the hole in the crown ring, the size of the hole at the small end of the taper in the body, the length of the cone (and body) and the number of slots in the cone.

Samples of the re-designed 3mm fittings were produced and tested. The performance was found to have improved significantly both in terms of breaking load and consistency. The average breaking load improved from 7045 N with a standard deviation of 592 N to 7955 N with a standard deviation of 62 N.

As with the 6mm compression fittings, the 3mm fittings have been found to reduce the breaking load of the cable by less than the termination method used by the wire manufacturer during their tests.

10. Further Work

- Consideration will be given to further understanding the effect of the number of slots by designing a special test rig to evaluate variations in cone design. Particular reference will be given to monitoring the forces required to achieve differing amounts of closure of the cone.
- A testing programme will be developed to determine more accurately the strength of the cable (as opposed to the assembly).
- Further work will be undertaken to improve the existing designs of the compression fittings and their effectiveness with particular reference to; the amount force the assembly is able to exert on the cable, by reducing the stress induced on the outer strands by the forward outer edge of the cone and removing redundancy in the design.
- Microscopic examination will be undertaken to obtain further information regarding cohesion and the ability of the fittings to hold the cable and also the failure mechanisms in both swage and compression fittings.
- Fatigue testing will be carried out on both the swage and compression fittings to determine how the terminations affect the cables in terms of their fatigue performance.

11. References

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Raouf, M & Kraincanic, I (1998). Determination of Wire Recovery Length in Steel Cables and its Practical Applications. *Computers and Structures*, 1998, vol. 68 445-459.