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The Influence of Rope Lateral Compliance on Winch Drum Design

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SYNOPSIS

The concept of rope load relaxation in conditions of multi-layering is re-introduced and its value in rational winch design is emphasised. Two distinct mechanisms are identified (those of Egawa/Taneda and of Torrance) and are compared for the benefit of the designer. Recommendations in favour of the former highlight the importance of the lateral properties of wire rope, the equivalent Young's modulus and Poisson's ratio. The Egawa/Taneda procedure is extended to take account both of the variation in lateral properties of wire rope with crushing stress and of 'thick' shells.

INTRODUCTION

When a single layer of loaded rope is wound close-coiled onto a winch drum it settles into place like a collar in a state of tensile stress, producing in the drum shell a corresponding compressive hoop stress. This compressive stress is usually calculated by treating the drum as a thin shell under uniform external pressure.

End supports and flanges are regarded as providing additional external stiffening and their contribution to general strength of the shell is usually disregarded when calculating its safe thickness. Moreover the variation of radial stress is generally ignored unless the shell thickness is more than about 10% of its diameter. The matter of thick shells will be returned to later in this paper.

If the amount of rope accommodated on the drum can be contained in one layer this simple calculation procedure based upon rigid statics holds good. However, if the loaded rope is wound in several layers, inner layers of rope relax in tension due to radial elastic deformations in the drum and rope system. Thus the pressure on the drum reduces to a value less than that resulting from the sum of the original loads in each layer.

Dr Maw is Principal Lecturer in Applied Mechanics in the Mechanical Engineering Department of Sunderland Polytechnic. His present research interests are the design and performance of heavy duty winches and cable lift systems, which are currently being investigated under his direction at Sunderland. In collaboration with his research assistants, Dr Maw is developing finite element techniques for winch design which also include the rope mass. Related interests are rope corrosion and health monitoring, wear and load redistribution of chain mooring systems on floating rigs, and the commercial advantage to be gained in winch design by properly accounting for rope load on the barrel.

Miss Karbalai graduated from Sunderland Polytechnic with a BSc in Mechanical Engineering in 1983. For the next three years she followed an approved research investigation into the design of winches with particular reference to multi-layering. This work, now completed, is being written up for a PhD and caught the attention of NEI-Clarke Chapman Ltd who appointed her as a design engineer in September 1986. Miss Karbalai is currently completing her training programme for CEng.

REVIEW

This characteristic of multi-layered winch barrel loading is recognised but not well understood. It was first suggested by Waters,[1] who proposed a mathematical model of some considerable sophistication including all the parameters likely to affect drum loading. Unfortunately the process of solving the model lay in abeyance for some thirty years until it was re-introduced by Egawa and Taneda.[2]

Following this, several attempts (eg Torrance[3]) were made to quantify the mechanism of rope load relaxation using 'slide rule' calculation procedures. Naturally these techniques lacked sophistication but their simplicity held appeal and, of these, Torrance's procedure is favoured in those few design offices where load relaxation is exploited.

Torrance models a multi-rope-layered winch barrel as a series of equal thickness concentric cylinders encircling the drum, each cylinder representing one rope layer. The thickness of the cylinders is arranged so that they possess the same elastic properties as the wire rope in its longitudinal direction. No account is taken of elastic changes in the rope in a radial direction.

When a second layer of loaded rope is wound on top of the first it pressurises the drum through the first layer and thus produces its own contribution to elastic compression in the shell. Consequently the first layer, now encircling a reduced diameter, experiences a decrease in its pitch circle and a corresponding reduction in circumferential strain.

The initial tensile load in the rope of the first layer is therefore reduced by a calculable fraction. If a third layer is added, the tension in the first layer reduces still further, and by the same process the tension is relaxed in the second layer. It is clear that when the last layer is added, the nett total pressure on the shell is the sum of the actual final loads in the rope layers but is less than the sum of the original winding loads in each layer.

Torrance quotes relationships from which these load reductions can be calculated. He takes account of the modulus of elasticity of the drum material and of the rope in the direction of the tension. These relationships are simple to use requiring only hand calculators for arithmetic work.

Egawa and Taneda, pre-dating Torrance, follow up Water's suggestion of an additional mechanism for rope tension relaxation by taking into account the lateral compliance of the wire rope itself. Their analysis of drum and rope deformation is much fuller than that of Torrance and includes all the additional relevant parameters — friction between coils, geometry of rope compaction and Poisson's ratio in the diametral direction. Friction, it is found, tends to reduce tension relaxation (unless the coils lie on top of each other, ie a Koepe drum) but the lateral elasticity of the rope itself emerges as the dominant parameter in relaxation calculations.

ROPE LATERAL PROPERTIES

The diametral modulus of elasticity, $E'r$, of wire rope does not appear in tables of rope properties nor does the diametral Poisson's ratio, $\nu'r$.

When a rope of diameter d is compressed between parallel flat plates with a load of W over a length L

$$E'r = \frac{W / L\,d}{\varepsilon_1} \qquad (1)$$

and

$$\nu'r = \varepsilon_2/\varepsilon_1 \qquad (2)$$

where ε_1 is in the diametral strain in the direction of the load and ε_2 is the diametral strain perpendicular to the load.

Figure 1 shows values of $E'r$ for a steel core wire rope, 5 mm nominal diameter and 7 x 19 construction crushed over a length of 6 in. Results for initial loading were ignored and those quoted are for the second cycle when values tended to settle. $\nu'r$ was found to be 0.36 ($E'r$ is quoted as kgf/mm² because that is accepted practice). At a stress of 30 N/mm² the value of $E'r$ is about 0.6% of the longitudinal Young's modulus, Er. The rope is very compliant laterally.

Figure 2 shows corresponding values for a steel stranded rope of nominal diameter 28 mm and 6 x 36 construction. $\nu'r$ was found to be 0.38.

It should be pointed out that the test results for Figs 1 and 2 were taken under conditions of zero axial load, conditions not pertaining in operation. Wire rope is made up of a series of wires and strands laid in a helical pattern and therefore it might reasonably be anticipated that the lateral compliance would reduce as the axial load increases.

Rather surprisingly tentative experiments carried out by the authors suggest that this is not the case and that axial load does not greatly affect values of $E'r$. However this needs further investigation by extensive experimentation.

APPRAISAL

Although very limited, all experimental work on the diametral properties of wire rope leads to the conclusion that, when a rope is wound onto a winch drum, it is much more compliant in the direction of the drum radius than the drum itself. Thus when outer layers of rope are added, the changes in pitch circle diameter of the middle layers are a function of the drum elasticity and of the rope longitudinal and lateral elasticity.

For a soft flexible rope these changes are much higher than those predicted by Torrance, who does not account for lateral

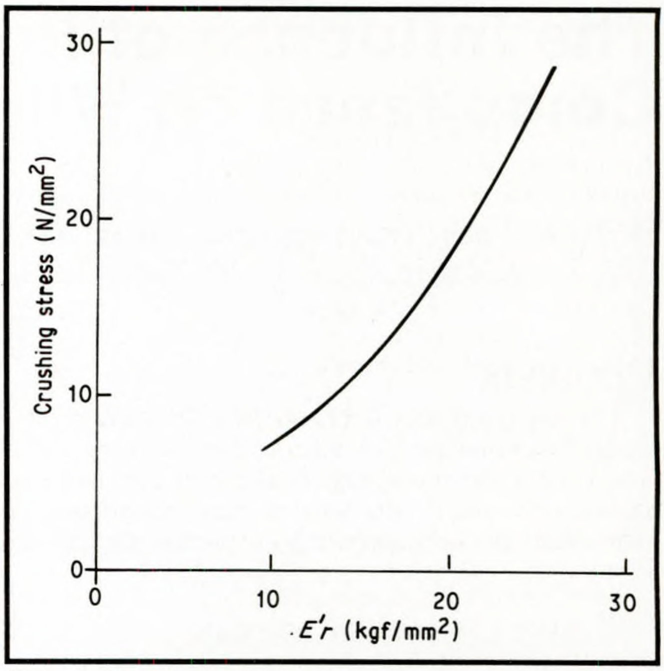

FIG. 1: Variation of diametral modulus of elasticity, $E'r$, with diametral stress, 5 mm rope

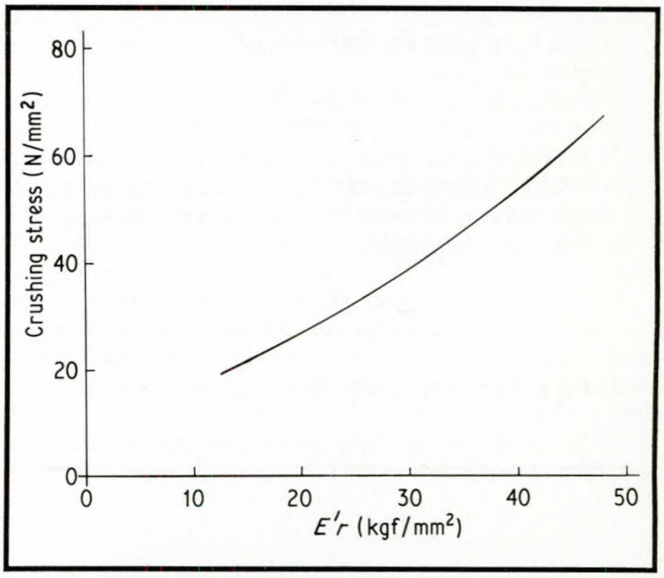

FIG. 2: Variation of diametral modulus of elasticity, $E'r$, with diametral stress, 28 mm rope

elasticity. However the Egawa and Taneda calculation procedure is considerably more complex than Torrance's involving, for N layers, the manipulation successively of (N–1) matrix equations of dimension (N–1), (N–2) etc. Therefore it is of considerable value to compare the two procedures in terms of design prediction.

It becomes apparent that the final drum load is influenced by two seemingly conflicting effects:

1. The hoop stress change in the Torrance model is influenced only by the reduction in barrel circumference as it deforms. All thicknesses remain constant so, for the same longitudinal elastic properties, the layers are stiffer radially on the Torrance model. Therefore sub-layers support outer layers better and thus produce on the drum a smaller nett hoop compressive load.

2. The rope layers on the Egawa and Taneda model, however, crush inwards so where the cross-compliance is high this parameter dominates the calculation and the rope load relaxation becomes very large.

The general relationships of Egawa and Taneda have been programmed by the present authors who have also extended the theory by incorporating Lamés equations to take account of 'thick' shells and variation of radial stress. Figure 3 shows the variation of nett drum load with $E'r$ for the locally built industrial winch whose specification is given in the appendix. The value for $E'r$ of 660 kgf/mm^2 is supplied by the rope manufacturer and leads to a nett drum load which is 78% of that obtained by simple addition of the original winding tensions in each layer.

For reference purposes Torrance's prediction is also included. Here the nett drum load is 71% of the accumulated winding tensions. Figure 4 shows the final loads in each layer, the top layer carrying the original load of 200 tonnes. The figure illustrates very emphatically the influence of the rope lateral compliance.

The final drum load is seen to be very sensitive to the value of $E'r$, which in turn is a function of the crushing stress on the rope. Here the designer is faced with a difficulty because the lateral stress distribution in the layers is not known a priori. Therefore neither are the values of $E'r$, themselves vital to the calculation.

To overcome this difficulty we must turn again to Egawa's and Taneda's analysis.

In a free end drum shell of thickness t and outer diameter D the radial compliance

$$Ao = \frac{D}{2\, t\, d\, Ed} \tag{3}$$

where Ed is the modulus of elasticity of the shell material.

When the shell is 'thick' the compliance is modified to

$$Ao = \frac{1}{d\, Ed}\left(\frac{R^2 + r^2}{R^2 - r^2} + \nu\right) \tag{4}$$

where R and r are the outer and inner radii. Also

$$A_1 = \frac{(1 + \sin\gamma)\,[2 - \nu' r \cot(\gamma + \delta)]}{2\, E' r_1\, (D + d)} \tag{5}$$

which is the radial compliance of the first layer of rope. γ is the angle of rope contact (usually 60°) and tan δ is the the coefficient of friction, μ. Finally,

$$\underset{(i=2\mathrm{to}N)}{A_i} = \frac{2 \sin\gamma\, [1 - \nu' r \cot(\gamma + \delta)]}{E' r_i\, \{D + [1 + 2(i - 1) \sin\gamma]\, d\}} \tag{6}$$

is the radial compliance of the ith rope layer from the second outward.

$$E' r_i = F(\sigma_i) \tag{7}$$

where σ_i is the crushing stress on layer i and is evaluated by

$$\underset{(i=1\mathrm{to}N-1)}{\sigma_i} = \frac{2}{D\, d}\left(P_{i+1} + P_{i+2} + P_{i+3} + \ldots + P_N\right) \tag{8}$$

and P is the rope load.

The calculation proceeds thus: a final load distribution through the layers is assumed and a value for $E'r$ is determined for each layer using equations (8) and (7). These values are fed into the Egawa/Taneda procedure via equations (3) or (4), (5) and (6) to produce a preliminary load distribution replacing that assumed. Subsequent re-iteration through equations (8) and (7) corrects earlier values. Convergence is rapid though computing time can be optimised by ensuring that assumed values for $E'r$ in the trial calculation correspond well to the maximum crushing stress likely to occur on the first rope layer.

Following the procedure closely, and using the empirical expression of equation (7) (see appendix), a recalculation for Fig. 4 corrrects the final drum load reducing it by only 1%.

DISCUSSION

Experimental research on winch barrels is sparse and information on the behaviour, in particular failure, under load of units in operation is very difficult to obtain. Bellamy and Phillips[4] conducted a fairly extensive series of experiments but

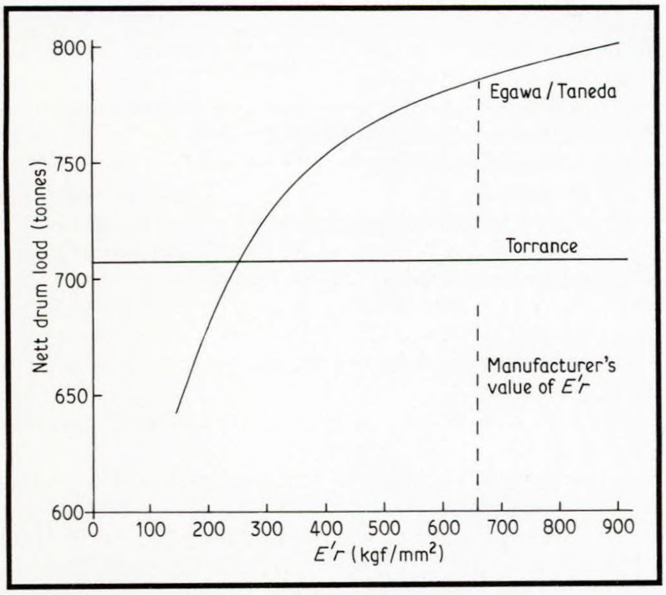

FIG. 3: Nett drum load plotted against *E'r* for the winch specified in Appendix

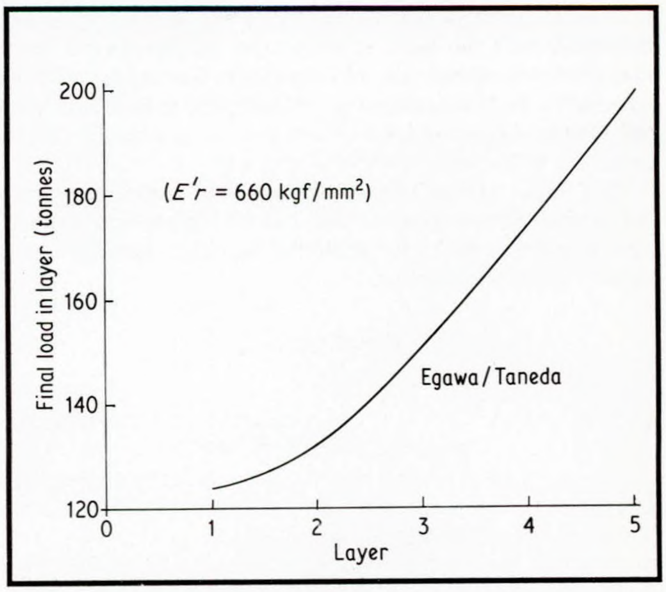

FIG. 4: Final loads in each layer for winch specified in Appendix

their attention was mainly centred on assessing the load and bending moment on the flanges. In addition, their conclusions are understandably specific to their own rig.

Egawa and Taneda performed a restricted experimental investigation in support of their analysis but the strength of their contribution to winch barrel research is undoubtedly the analysis itself which quantifies very thoroughly Water's earlier work.

The present authors have experimented on a small multi-layered winch using strain gauges and have performed a finite element analysis developing a technique for taking rope load relaxation into account.

All researchers are agreed on the point that relaxation of rope load is significant on winches carrying several layers. The present authors are able to add the following observations:

1. The majority of multi-layer winch barrels currently in operation were designed without taking rope tension relaxation into account. The rest were almost exclusively designed using Torrance's procedure.
2. Experienced designers, using rigid statics procedures to analyse the shell hoop stress, are aware that they can (Classification Societies permitting) work with very low safety factors. This suggests that hoop stresses are much less than those predicted.
3. The rope lateral elasticity modulus is much less than Young's modulus for the shell material. Considerable compaction and subsequent elastic compression of rope must therefore occur.
4. No case of drum failure by elastic instability of the shell (buckling) is reported.
5. Experience with the Egawa and Taneda model shows that, on a winch barrel carrying many layers of loaded rope, the layers in the central mass lose all tension and can, in extreme cases, be subjected to hoop compression.

These five points lead inescapably to the conclusion that winch barrels are currently over-designed. There is, of course, certain comfort in this for winches transporting personnel but it does carry severe commercial penalties.

The cost of a winch rises very sharply with the thickness of the drum shell so any mechanism which sensibly defines loading should be thoroughly understood and exploited if the industry is to remain competitive. As an extreme example of this, there is a threshold beyond which plate rolling has to be sub-contracted abroad. By applying the design principles described here the authors were able to convince a local manufacturer and his customer that the shell thickness could be reduced by 15%, thus enabling the shell plate to be rolled in the UK. The saving in cost and weight gave a commercial advantage.

The only procedure which takes all rope and drum parameters into account is that due to Egawa and Taneda, modified if necessary for thick shells, and re-iterated by the present authors' technique.

CONCLUSIONS

Much experimental and theoretical work remains to be done on rope lateral compliance, and on the effects of lubrication, axial loading, crushing and type of rope bed (plain surface, grooved or rope to rope). Also the influence of supports and flanges needs to be investigated thoroughly by relaxation finite element methods backed up by careful experimental stress analysis.

Nevertheless experimental and other relevant investigations that have been undertaken suggest that very substantial savings can be made by adopting sensible rope load relaxation procedures.

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APPENDIX

Parameters relating to the winch barrel analysed for Figs 3 and 4

Numbers of layers, N	5
Angle between rope centre, γ	60°
Drum thickness, t	120 mm
Drum Youngs modulus, Ed	21 000 kgf/mm^2
Coefficient of friction, μ	0.09
Solid cross-sectional area of rope, a	3200 mm^2
Loading tension, P	200 tonnes
Drum diameter, D	1680 mm
Rope diameter, d	84 mm
Rope longitudinal modulus of elasticity, Er	7500 kgf/mm^2
* Rope diametral Poisson's ratio, $\nu'r$	0.36
* Rope diametral Modulus of elasticity, $E'r$	660 kgf/mm^2
* $E'r = (\sigma - 0.563)/0.169$ kgf/mm^2	[see equation (7)] (σ in N/mm^2)

(*Manufacturer's Values)

Discussion

Dr C. R. CHAPLIN and **A. E. POTTS** (University of Reading): The problem of winch drum design which is addressed by this paper is one of great practical interest, especially where rope is wound onto a drum at such extremes of tension as in the example referred to by Dr Maw and Miss Karbalai. We are aware of at least one instance of a drum operating under very similar circumstances being subjected to such high radial loading that it is plastically extruded at the ends — this is clearly one example of a winch drum which was not over-designed. As far as design is concerned, it may well be that, rather than over-design, the low incidence of failures is due to the fact that winding on the full drum capacity at the maximum design load is a very rare event.

This paper has taken the theory published by Egawa and Taneda[1] and, using some rather unusual values for transverse rope stiffness, calculated the radial loadings for one specific case. There are several important issues raised by this paper which must be discussed. The points to be considered include:

1. Published work on this topic, which the present authors have overlooked.
2. Problems in the fundamental Egawa and Taneda theory relating to the essentially three-dimensional nature of the problem and the highly anisotropic nature of a wire rope.
3. The confusion introduced by the use of inconsistent values for transverse stiffness.

Experimental work on winch drums has been carried out by a number of different investigators, but in particular Dolan,[2] Piggott[3] and Dietz[4] have made extensive studies. All three of these publications provide extensive data on winch drum stresses, which hardly constitutes information being 'sparse' and 'hard to obtain'. Dolan also details a number of service failures of winch drums in South African mines over a 50 year period.

On the issue of design procedures which take account of the radial compaction of both the drum and the rope, it should be noted that in addition to the work of Egawa and Taneda, Sang et al.[5] and also Dietz have taken these factors into consideration. Dietz also reports an extensive series of tests to measure transverse rope stiffness. These tests were performed with a range of rope constructions and sizes, with ropes subjected to different levels of axial tension and different loading arrangements, including tests with ropes stacked on top of each other to simulate the layers on a drum.

The analysis used here has, as the authors acknowledge, been taken directly from Egawa and Taneda. However, the transverse stiffness term, $E'r$ and the diametral strain ratio term, $\nu'r$ have been defined by Dr Maw and Miss Karbalai as material constants, namely the 'diametral modulus of elasticity' and the 'diametral Poisson's ratio'. This is quite inappropriate since what we are dealing with is not a material as such but a structure, and a structure in which the response to external loads involves significant geometrical changes (there are some parallels with a highly anisotropic oriented composite material, which serveone help to understand some of the relationships between load and deformation in mutually orthogonal directions).

Furthermore, one would not expect to measure the elastic modulus of a material from the ratio of load to displacement across the diameter of a cylinder. The definition presented for Poisson's ratio also shows a lack of sensitivity for the fundamentals of elasticity. Egawa and Taneda were very careful to define these two terms as 'the ratio between the compressive force per unit length of the rope and the decrement of the rope's diameter' and 'the increment of the rope's diameter perpendicular to the force and the decrement of the rope's diameter in the direction of the force'. However, both they and the authors of this paper have failed to appreciate that the direct measurement of this behaviour does not translate into the prediction of deformations under the influence of the more complex sets of forces which they describe between the layers of rope on a winch drum. The reason for this is that the transverse deformations of the rope are derived from internal geometrical changes rather than simple elasticity. The nature of this behaviour is apparent from the highly non-linear relationship between transverse load and displacement.

Another important relationship which the present theories appear to have neglected is the influence of axial load on rope diameter. The combination of a high axial stiffness, a low transverse stiffness and the helical nature of the rope geometry lead to a situation whereby changes in axial load produce significant changes in diameter, whereas transverse loads have an insignificant effect on rope length. The implications of this behaviour as regards the theory developed by Egawa and Taneda is that their method will underestimate the drum loading since the relaxations they calculate for rope tension will in turn lead to a recovery of rope diameter offsetting, to some extent, the crushing previously determined. The magnitude of this component has not been evaluated but it is unlikely to be negligible, although probably smaller than errors introduced through the use of an inappropriate stiffness model.

The measurements of lateral stiffness (diametral modulus of elasticity) reported by Dr Maw and Miss Karbalai have presumably been obtained from experiments in which a short length of rope is crushed between flat parallel plates. The values indicated in Figs 1 and 2 are of the same order as those reported by other investigators using similar methods.[1,4,5] However, the extensive series of tests reported by Dietz indicates not only that lateral stiffness is appreciably reduced when considering a stack of rope samples (by factors of two or more at low loads) but also that there is a significant enhancement due to axial tensioning of the rope, in contradiction of the 'surprisingly tentative' experimental results referred to by Dr Maw and Miss Karbalai.

Song et al. have pointed out that the loading mechanism on a section of rope trapped between outer and inner layers on the winch drum is very different from the simplified diametral loading case (and also from Dietz's stack). The general case of the rope surrounded by six near neighbours in Lebus systems will result in a set of four compacting forces in almost radial directions and at more than 30° to the vertical. This combination will be more restrictive on internal rope geometry changes than the unidirectional crushing, and more so than would be predicted by any so-called Poisson's ratio effect. The result, as far as the Egawa and Taneda theory is concerned, is an enhanced stiffness resulting in higher drum loading. What is clearly needed here are some carefully designed experiments which can more adequately model the transverse loading mechanism and obtain directly applicable stiffness measurements.

Another factor identified by Song et al. which influences stiffness in general is the progressive change taking place during the life of a rope. As a rope is used a general 'bedding-in' process occurs. This involves both a geometrical balancing of the construction and local wear at inter-wire contact points. This process, which proceeds fairly rapidly in the early stages of life, results in a further enhancement of stiffness. The effect is readily measurable in the axial direction and is fairly small (of the order of only a few percent) but in the transverse direction, where one would expect to find more significant changes, we are aware of no published data.

Finally we turn to a consideration of the values for transverse stiffness actually used by Dr Maw and Miss Karbalai in their calculations. They have taken a value of 660 kg/mm^2, which although an order of magnitude higher than their highest experimental values, two orders of magnitude greater than the value used by Egawa and Taneda, and significantly greater than any values either assumed or measured by any other authors, has excited no comment. This is rather perturbing. They have made calculations, in common with previous authors,[1,5] indicating the influence of transverse stiffness on drum loading, but even here the lowest value used is significantly greater than the experimental values plotted and those used by other authors. Another area of concern here is the origin of the empirical expression presented for transverse stiffness, which bears no relationship to the experimental plots. This apparent overestimate of lateral rope stiffness is likely to have a greater influence on the calculated drum loadings than any of the qualifications discussed above.

From the above discussion it is apparent that, apart from the specific difficulties arising from this particular paper, one cannot help feeling a certain lack of confidence in the published design procedures which allow for a reduction in drum pressure as a result of transverse rope compliance. To restore confidence there is a clear need for a thorough study of transverse rope deformation which takes due account of the loading mechanism applied to a rope on a winch drum, and also models the interaction with the falling axial tension as the number of layers and the radial load increase.

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Authors' reply

We should first like to thank to Dr Chaplin and Mr Potts for a very careful perusal of our paper. We note that their comments concentrate heavily on Dr Chaplin's interest in wire rope technology and, since this was not the central theme of the paper, we feel that the discussion might divert attention from the main aims, which were:

1. To encourage designers towards an awareness that the lateral compliance of wire rope bears significantly on final drum loading and therefore its cost and weight.
2. To illustrate that the lateral stiffness of wire rope varies greatly with different types of rope and different crushing stress, and that it is likely to be non-linear.
3. To highlight for designers a useful predictive procedure (in classical mechanics) for estimating the drum load.
4. To show how variation in $E'r$ can be incorporated into the calculation.
5. To urge more applied research.

Also, in view of the critical nature of the discussion, it is worth stating what were not the aims of the paper.

It was not intended to be a review of research into wire rope properties, and it was not the primary intention to report our work on lateral properties. The experiments reported in the paper describe only a small part of the experimental work that we have carried out, and it is included as necessary background support.

We considered and referred to published work only when we felt that it provided relatively simple and directly applicable material. Thus we did not, for example, include Dolan because his paper is based on a survey which was completed 25 years ago. Waters, on the other hand, we did mention, because he addressed the principles of the problem and his work was used as a source reference. A similar very comprehensive survey to Dolan by Atkinson and Taylor (*Colliery Engineering*, 1967) was omitted for the same reasons.

It is regrettable that we missed the German paper by Dietz because it would appear that we might therefore have done some unnecessary background work. Lack of time precludes a discussion of how the work of Dietz would impinge upon the present paper; however, from the remarks of Dr Chaplin and Mr Potts, it seems that Dietz's work might provide useful design data, and we thus wonder why it has not filtered through to design offices.

The paper by Piggott was about colliery winders. It is not uncommon for these to carry two layers of rope but never more than two, so Piggott's work was not relevant to our paper.

It was also not intended to highlight modes of failure of winch barrel assemblies. Our comment (no. 4 in the discussion) refers specifically to elastic instability of the drum. Certainly failures of different kinds can occur, and the example quoted in the opening remarks of the discussion is one, but there are others, and designers should be wary of them. The extreme loading experienced on high-duty multi-layered winches brings new problems, for example flanges bursting due to rope axial thrust, local plastic deformation of the drum shell under the first layer, cold welding of the lower rope layers, tearing of strands and fretting of wires, bearing failure due to axial elongation of the drum, etc. Our suggestion that, despite all these potential hazards, winches might be over-designed is hardly answered by the speculation that loading rarely reaches the maximum design value. The winch will have been tested at least to its full design duty and, in offshore applications, a repetition of that load is unlikely to be a rare event; it is much more likely that unforeseen circumstances lead to overload.

We made the important point, which does not seem to have been made elsewhere, that Egawa and Taneda took the rope lateral elasticity modulus to be constant. Experimental work done by us (and it seems by others) shows that this is not the case and that the procedure for calculating nett drum loads proposed by Egawa and Taneda needs modification if it is to take account of this and non-linearity. We explained our modus operandi. However, as a precursor to this, knowledge of the rope lateral properties is necessary, either on the basis of a simple representation (Egawa/Taneda and the present authors) or as a more complex representation (Song et al.). It appears sensible, with the present state of the art, to use a simple representation which can easily be measured on a test length of rope. There is no point in introducing sophisticated rope models until there is reliable statistical information on the behaviour of winch barrels whose design has included rope load relaxation calculation

Values for transverse rope stiffness quoted in the paper are specific and experimental. The sizes were chosen partly because of availability, partly because they illustrated differences in lateral properties, and partly because the smaller sizes were used in a subsequent experimental investigation on a small winch. The value of 660 kgf/mm^2 used in the sample calculation was the winch builder's quoted value on a rope of foreign manufacture, and it excited no comment because we were not (and still are not) surprised at very large differences in $E'r$ for ropes of differing size and construction. However, if the value quoted was incorrect and too high, as Dr Chaplin and Mr Potts suspect, then the rope load relaxation is even greater than that predicted in Fig. 3, lending further weight to our contention that designers neglect consideration of $E'r$ at their cost.

The empirical formula, to which Dr Chaplin and Mr Potts take exception, was supplied by the manufacturer, and certainly bears 'absolutely no relationship to the experimental plots' because it applies to a rope of 84 mm diameter, whereas the plots are for 5 and 28 mm rope. Application of the formula yields a crushing stress of about 112 N/mm^2, which is near enough that sustained by the first layer of rope at the 780 tonne drum load as depicted in Fig. 3.

On the matter of transverse stiffness and the non-isotropic nature of wire rope, Dr Chaplin and Mr Potts raise several points for debate.

They state that $E'r$ and $v'r$ as, as we define them, are not material properties. This was recognised at an early stage of our research, hence the fact that the stated values of $E'r$ and $v'r$ in the paper are related to specific structures (Figs 1 and 2). It is clear that Egawa and Taneda used long written definitions, quoted by Dr Chaplin and Mr Potts, for $E'r$ and $v'r$ more for reasons of lucidity than semantics (as indeed have other researchers) to distinguish them from, for example, the 'longitudinal' property, Er.

Dr Chaplin and Mr Potts assert that the influence of axial load on rope diameter is neglected in present theories, and that rope load relaxation will be less than that predicted by Egawa and Taneda, due to falling axial load in sub-layers. We agree that this is a possibility, and went some way towards testing it when we experimented upon a small multi-layered winch carrying 5 mm diameter, 7 x 19 wire rope. At a rope tension of 60% minimum breaking load, the crushing stress on the first layer, when the second was added, reduced the diameter of the rope by about 8%. This reduction was inferred from separate tests in which $E'r$ was measured.

The Egawa/Taneda calculation predicted a corresponding fall in first layer axial rope load of about 20%. A second series of tensile (axial) tests on the rope showed that diametral recovery from 60% MBL by 20% of that value was about 0.2%. The recovery in diameter was therefore some 2.5% of the original reduction due to crushing. We regarded this as a second-order effect; moreover tests on diametral recovery were conducted on a free rope not surrounded by other compacting ropes. It seems unlikely that diametral changes will be fully reversible in the circumstances of complex compaction in sub-layers on a winch drum. The matter of diametral recovery will be returned to later.

The general case of compacting forces on a typical rope, which Dr Chaplin and Mr Potts assign to Song et al., was in fact studied earlier by Egawa and Taneda, who also showed that there are four crushing forces inclined at 30° (plus the friction angle) to the vertical. It is incorrect to say that the Egawa/Taneda theory involves unidirectional crushing.

Dr Chaplin and Mr Potts state that there are some parallels with a highly anisotropic oriented composite material which serve to help one understand some of the relationships between load and deflection in mutually orthogonal directions. We have also recognised this fact and have modelled the rope as an orthotropic structure (or composite). We did not report this work in the present paper because we did not consider it relevant to the main aims.

While we have been criticised by Dr Chaplin and Mr Potts for experimental procedure in the measurement of lateral properties (and in the fundamentals of elasticity theory), nonetheless they have also stated that the experimental values of Figs 1 and 2 are of the same order as those reported by other independent investigators using similar methods (Egawa/Taneda, Dietz, etc). Does this independent work not support our procedures rather than single them out for criticism?

We are further stated to have failed to appreciate that direct measurement of rope lateral properties does not translate into prediction of deformations under the complex system of forces between rope layers on a winch drum. There are two perturbing aspects to this statement.

First, what experimental evidence do Dr Chaplin and Mr Potts have to say that directly measured properties do not translate? They later admit that carefully designed experiments are needed around the Song et al. and the Egawa/Taneda theories. Surely there is a contradiction here. Secondly, as the statement applies to our work, it is simply not true. We have persistently expressed the view that lateral properties would be better measured under conditions appropriate to a winch barrel. The more obvious of these is that rope curvature and bending will influence results, but there are other conditions, for example friction, cyclic loading, type of rope bed. We agree that the system cannot be fully described by simple elasticity but, to get research up and running, a start has to be made, and published work on the behaviour of wire ropes in the conditions described above is virtually non-existent.

Equation (1) and the paragraph thereafter in the paper explain clearly how we determined lateral stiffness, but we also undertook experiments on compliance of wire stacks. Results of these experiments were not included because, as we have stated, experimentation into cross properties of wire rope was not the main point of the paper. However, we found that there is not a linear relationship between compliance of one layer and, say, three layers (it is not three times, for example). Also, we have not properly addressed the problem of Lebus types of rope bed. Some useful remarks are made on this by Bellamy and Phillips, and the authors agree with Dr Chaplin and Mr Potts (and with Bellamy and Phillips) that grooved rope beds lead to higher nett drum loads.

The bedding-in process, which Dr Chaplin and Mr Potts say was identified by Song et al., is well known in design offices and it is accommodated in colliery practice. It was very much in our minds when we measured lateral stiffness. As we say in the paper, first cycle loading was ignored and results for the second cycle were recorded for Figs 1 and 2. Most of the bedding-in process occurred on the first cycle but, when the same ropes were tested again a day or so later, marginal recovery was noted. The extent of recovery was found to depend on the rate and magnitude of initial loading. Both the 5 and 28 mm ropes were tested in this way.

This interesting fact side-tracked us, and we repeated the experiments with locked-coil rope, but this was found not to bed-in and settle until the third cycle.

To return to a point discussed earlier: contrary to Dr

Chaplin's and Mr Potts' speculation, it is probable that, because of this bedding-in process, falling axial load in sub-layers will have little effect upon diameter recovery and therefore little effect on radial load increase. In our experiments on a small but heavily loaded winch, we obtained evidence which suggests that Egawa and Taneda overestimate nett drum load by about 4.5% when six layers have been added.

Dr Chaplin and Mr Potts say that they are aware of no published data on the influence of bedding-in on transverse stiffness. This amply justifies the decision to conduct our own investigation because, as they suspect, we did find significant variations in lateral properties due to settling in.

We are grateful for the opportunity to have responded to a thorough and scholarly discussion, although we feel that the central themes of our paper have not been properly addressed. The comments have been directed more at side issues, many of which are the subjects of ongoing research.

We are also disturbed at Dr Chaplin's and Mr Potts' dismissive attitude to the work of Egawa and Taneda which, until experimental evidence proves otherwise, supports a comprehensive predictive procedure for estimating rope load relaxation.

Research into wire rope technology has been in progress long enough now for designers to expect that useful applicable data should be available to them in easily assimilated form. In these days of CAD/CAM and Expert Systems, this is even more urgent. The relatively simple analysis of rope load relaxation by Egawa and Taneda, exemplified in our sample (though typical) calculation, shows that a 22% reduction in predicted drum load might be expected by using their methods rather than simple rigid statics. Surely savings of this kind are worth pursuing.