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Development of Natural Rubber Bearings Laminated with Non-metallic Materials

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Development work has been carried out on natural rubber (NR) bearings reinforced with a range of non-metallic materials. The best composite system developed is NR/Aramid, bonded with a proprietary adhesive. An equation has been developed to calculate the limiting stress which could assist in the design of rubber bearings which comply with engineering specifications.

Natural rubber (NR) has been used in engineering applications since the middle of the nineteenth century, as illustrated by *Figure 1* which shows vulcanised rubber springs used for the primary suspension of horse-drawn wagons in 1850. In 1890 a 25 mm-thick rubber block was used to support a railway viaduct in Melbourne, Australia *(Figure 2)*. The original NR pads are still in service and are functioning adequately.

The design of such rubber blocks was very simple, so also was their chemical composition. Modern rubber bearings are more sophisticated; they are usually rubber/steel composites. The steel component can be external to the rubber or embedded inside it. In the case of externally-laminated units, steel sections bonded to the external faces of the rubber serve to provide a means of positively locating the bearing; this

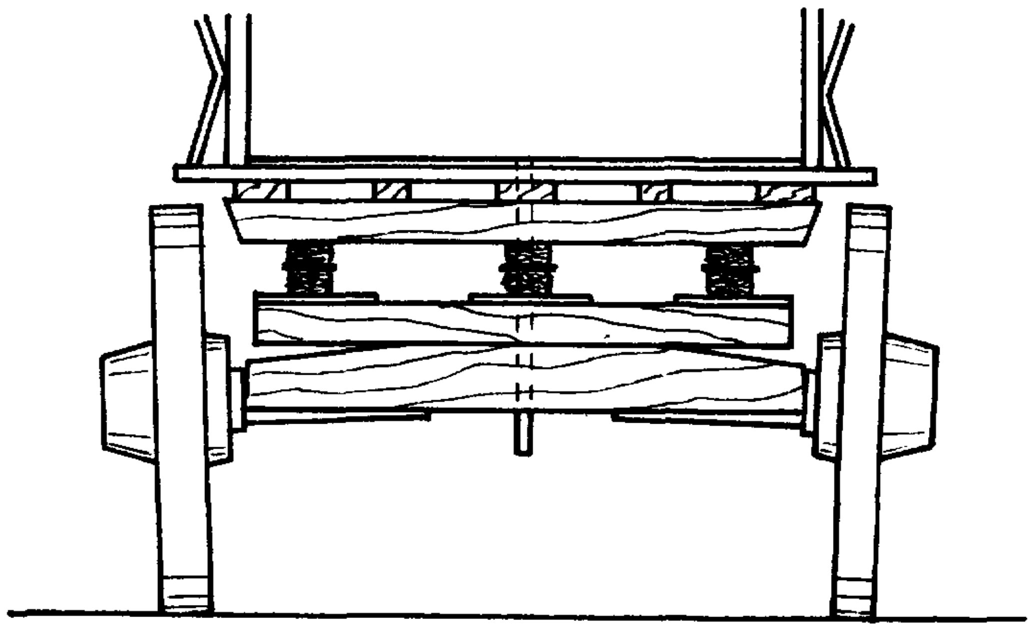

Figure 1. Rubber springs for dray wagon supplied by a Bradford-on-Avon mill from 1850.

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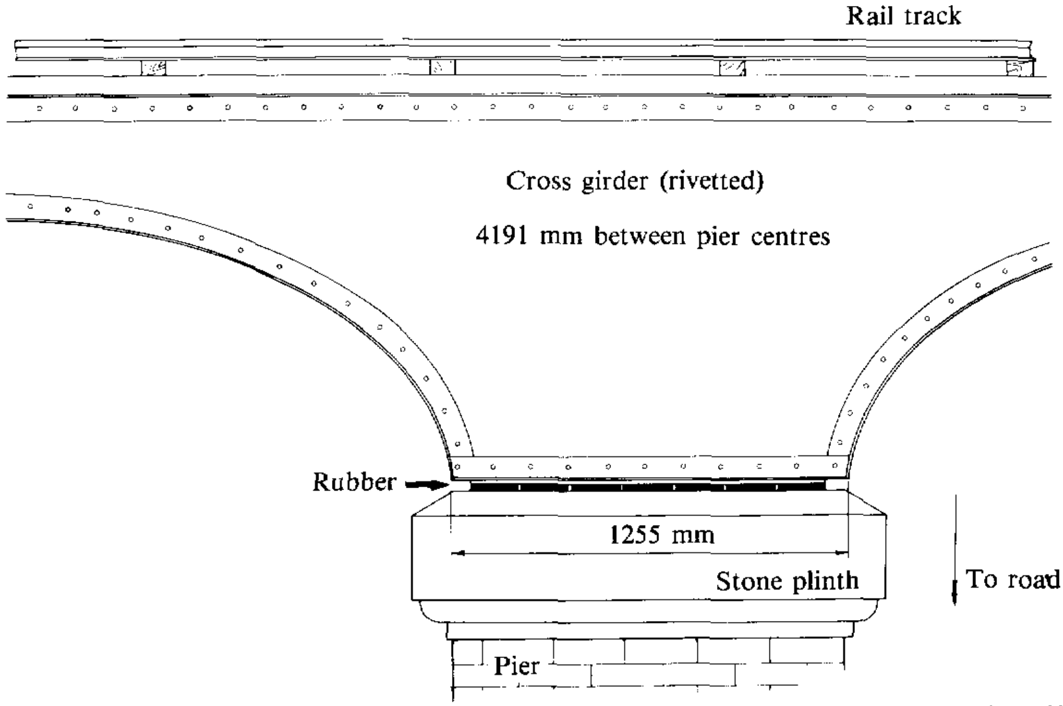

Figure 2. Flat NR pads installed in 1890 as structural rubber bearings supporting a railway viaduct in Melbourne, Australia.

is particularly important when the spring occasionally goes into tension, as in the case of car engine mounts. External metal fittings are also used when bearings operate in shear, where the load must be applied tangentially to the face of the rubber. Such external fittings must provide adequate stiffness in extension and bending for the intended application, and they must be well-bonded to the rubber. Traditionally, these fittings are made from mild steel, but there is no fundamental reason why other materials could not be used. In similar situations, thermoplastics are replacing steel, with savings in cost and weight.

In addition to external fittings, many rubber bearings contain internal steel laminations which provide a means for controlling the compressive stiffness of the unit without significantly altering the shear stiffness. Compression of a rubber pad whose loaded faces are not free to move, either because of friction or because they are bonded to a rigid material, forces the rubber to bulge at the perimeter of the pad. Formation of the bulge causes internal shear stresses to be generated within the rubber, and these cause the compressive stiffness to increase. For circular pads of constant thickness, the apparent Young's modulus of the rubber is proportional to the square of the diameter[1], and bonding the loaded face can cause the apparent Young's modulus to increase by up to a thousand-fold. As restriction of the loaded faces has no influence on the shear stiffness it is possible to vary the ratio of compressive to shear stiffness over a very wide range by incorporating a number of rigid layers inside the rubber.

This ability to control independently the stiffness of a rubber unit in different directions is widely exploited in situations where a bearing has to support a large mass, yet be very soft in horizontal planes. Such requirements are found in the large bearings used to support buildings, to protect them from ground-borne vibrations produced, for example, by railways or earthquakes[2]. *Figure 3* shows a typical steel-laminated bearing.

Advantages of Non-metallic Laminates

Current types of building bearing are variants on the bearings used to support bridges, developed during the 1950s. Early bearings were conservatively designed and used fairly massive steel plates to control the vertical stiffness. Subsequent experience has shown several deficiencies in this type of construction: these are particularly important in the design of building mounts.

Thus the life of such bearings is limited by corrosion of the steel plates; to limit this, rubber covers are moulded onto the laminated, load-bearing rubber. If the cover is vulcanised as part of the bearing it becomes difficult to position the steel plates as there is no means of positive location. Consequently, such bearings must be constructed by the compression-moulding of accurately made rubber blanks. This is a slow, labour-intensive process.

Another disadvantage of conventional steel-laminated bearings becomes very evident in the situation where a complex building mounting system has to be designed. In order to provide efficient vibration isolation and to distribute loads evenly each bearing should, ideally, be tailored to the loading conditions of the substructure it supports. A large building may require tens or even hundreds of different types of bearing, and the use of individually moulded bearings would greatly increase the total cost because each bearing would require a separate and expensive mould to be made.

There is no way round this problem with steel-laminated bearings. It would be possible to achieve more precise matching of the load characteristics if the bearings could be cut from a large sheet. The need to protect the steel, coupled with the difficulty of cutting rubber/steel laminates, preclude the use of steel laminates in this way but it should be possible if other rigid materials are used. Indeed, there has been some use of fabric-reinforced rubber bearings, but these are currently limited to synthetic rubber-based bearings[3].

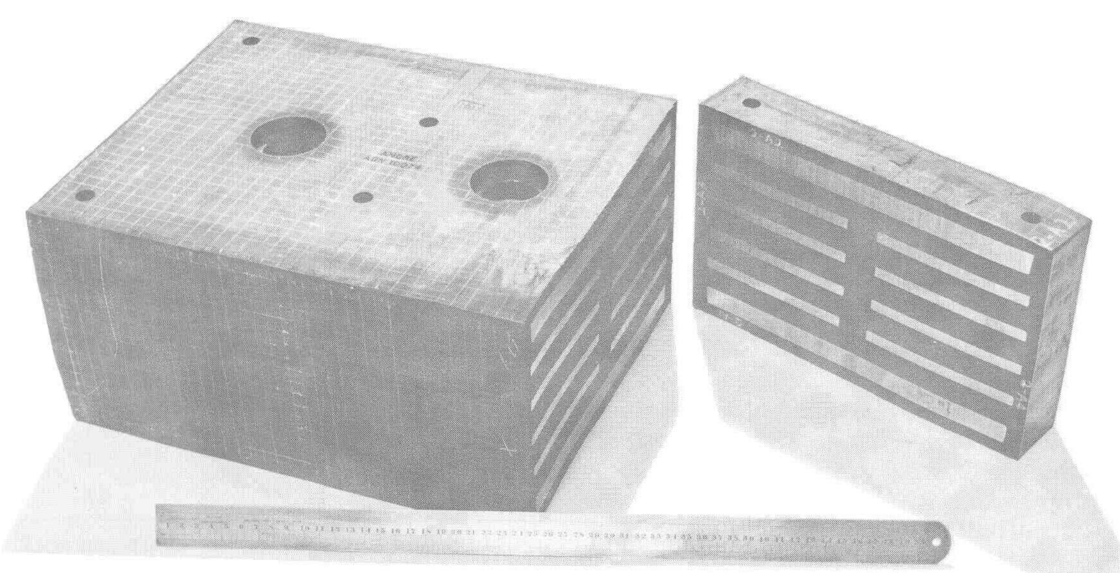

Figure 3. Sectioned NR bridge bearing.

Glass fibre-reinforced polychloroprene bridge bearings are used in the USA, and increasing interest in such units is being shown in Europe. Similarly, building mounts cut from nylon or glass-reinforced rubber pads are also used[4]. The need, therefore, is to develop NR based bearings in which the internal laminations are made of some material other than steel.

Bonding of Natural Rubber to Non-metallic Laminates

In order to develop non-metallic laminated bearings it is necessary to establish appropriate techniques for bonding NR to non-metallic materials. Studies have been carried out with fabrics of glass fibre and Aramid fibre ('Kevlar': Du Pont), using seven proprietary thermoplastics. Glass fabric was the first and obvious choice because it has been successfully used as a laminate in polychloroprene rubber-based bearings. Preliminary experiments suggested that a resorcinol/formaldehyde/latex (RFL) adhesive system, similar to that used to bond rubber to cords in the fabrication of tyres, satisfied the ASTM[5] strength criterion of 5.2 kN per metre in bond strength over a long period, but the bond was rapidly degraded by exposure to salt solution: six months' exposure reduced the bond strength to below the required value.

Taking the view that the poor performance of RFL-bonded laminates in a salt water environment ruled out this system, work was then carried out using (a) a proprietary adhesive (Chemlok 402), (b) a dry bonding technique, (c) the graft copolymer of NR with polymethyl methacrylate (Heveaplus MG), and (d) pretreatment with silane coupling agents. Of these, the Chemlok system has emerged as the most satisfactory, performing adequately in salt water tests.

The properties of Aramid polymers suggest that they are ideal materials for use in bearings. They are stiffer and stronger than glass fibre, and are less dense, though this economic advantage is offset by their slightly higher price. It was found that a proprietary Aramid (Kevlar) bonded very well with NR when the adhesive Chemlok 402 was used. The bond strength was unaffected after prolonged exposure to salt water.

The load-bearing capacity of fabric-reinforced bearings is limited by the strength of the fabric: if higher capacities are required it will be necessary to use a solid reinforcement such as one of the engineering-quality thermoplastics. Seven such thermoplastics were tested: Nylon 66, polyether ether ketone, polyether sulphone, polyimide, polyarylamide, polybuylene terephthalate, and polyphenylene sulphide. With all, good adhesion to NR was achieved using Chemlok 220. Of these, Nylon 66 (or other polyamides) are likely to be the best choice on cost grounds.

EXPERIMENTAL

Construction of Rubber Laminates

Rubber/fabric laminates were made from a NR formulation as shown in *Table 1*. The laminates were constructed by compression moulding various thicknesses of rubber on either side of the adhesive-coated fabric in a frame mould. *Figure 4* shows fabric rubber bearings of dimension approximately 230 mm square and 30 mm high, with Chemlok 402 as the adhesive.

TABLE 1. RUBBER FORMULATION

Item	Parts by weight
Natural rubber SMR CV 60	100
HAF (N-330)	45
Zinc oxide	2
Stearic acid	2
Antiozonants HPPD	2
Miccrystalline wax	2
Sulphur	2.5
CBS	0.6

Laminates were vulcanised for 45–120 min at 150°, depending on the thickness. The shear modulus of the rubber was approximately 1 MPa and the hardness was 69 IRHD.

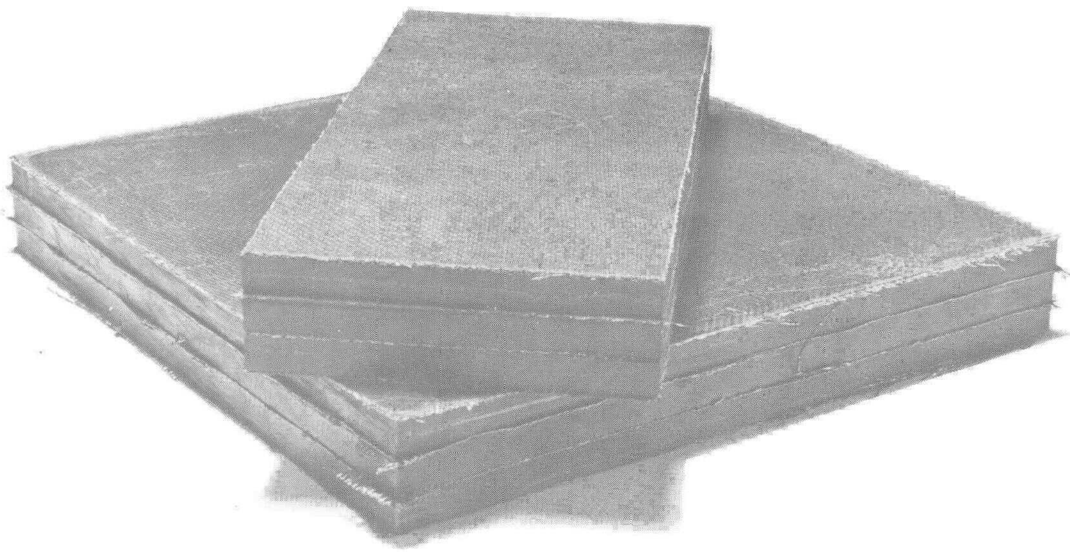

Figure 4. Examples of bearings comprising NR/fabric laminates.

Relationship between Peel Load and Shear Strength

In assessing various adhesive systems, it was assumed that the 180° peel test gave a good indication of bond strength in other modes of deformation. In bridge bearings, loads are subjected to combined compression and shear and it is essential to know if the results from a peel test correlate with failure stresses in this mode of deformation.

The tearing energy in simple shear[6] is dependent on the size of the propagating crack, whereas in a peel test the tearing energy is independent of crack size[7]. The effect of crack size may be particularly important in fabrics where a transverse thread may act as a flaw. The relationship between peel load and shear stress at failure has therefore been investigated. Laminates consisting of a single layer of fabric sandwiched between two 6-mm NR layers were used to construct quadruple shear testpieces as shown in *Figure 5*. The plan dimension of the testpiece is 25 × 50 millimetres. The testpieces were bonded to mild steel end plates using cyanoacrylate adhesive. They were subjected to a compressive strain of 5%, then deformed in shear at a rate of 10 mm per minute until failure

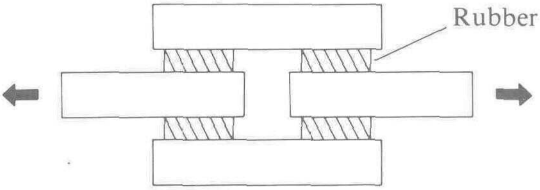

Figure 5. Quadruple shear testpiece.

occurred. This invariably resulted in separation of the rubber from the fabric rather than tearing of the rubber. Samples cut from the laminates (using a sharp knife) were 180° peel tested on 25 mm wide strips. The experimental arrangement is shown in *Figure 6.* The grip separation rate was 50 mm per minute. Peel loads were taken as the maximum load obtained at a steady rate of peeling.

RESULTS AND DISCUSSION

A simple relationship was found between the peel load and the shear stress at which failure occurred, subject to one restriction *(Figure 7).* When tearing into rubber took place in the peel test, the shear at failure was considerably lower than expected. The peel test can therefore provide a reliable guide to failure stresses in shear

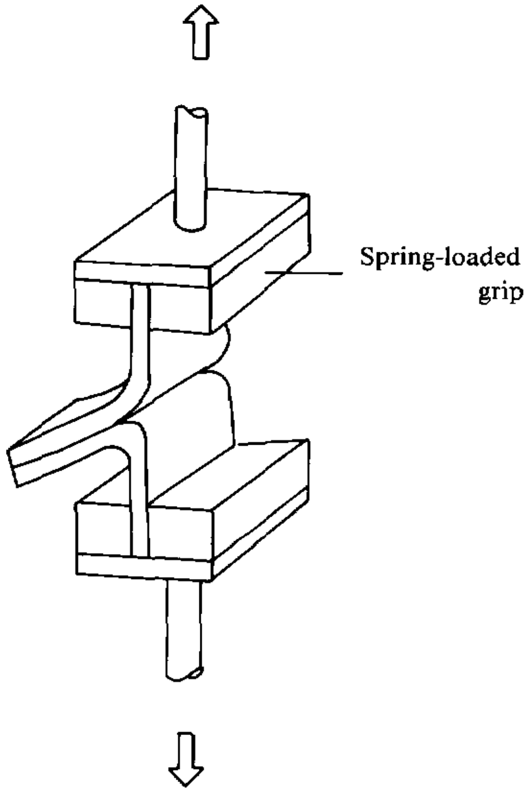

Figure 6. Arrangement for peel testing at 180°.

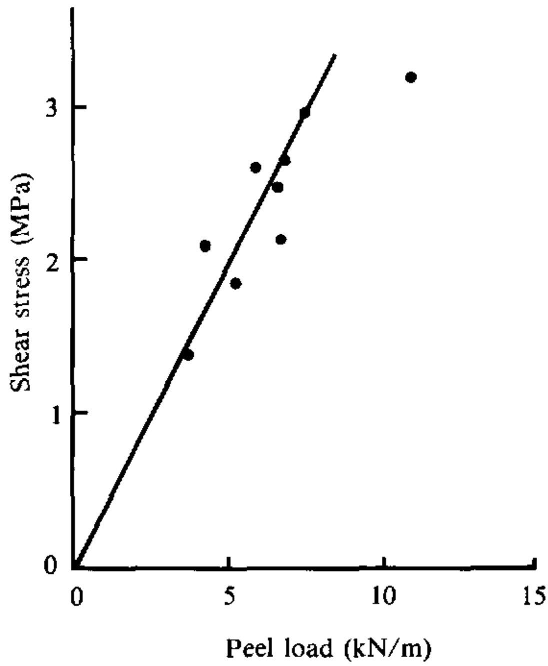

Figure 7. The relationship between peel load and shear stress at failure for glass and aramid fabrics.

provided the locus of failure is the same. The peel load accepted in the present specifications for fabric-reinforced bridge bearings (5.2 kN per metre) corresponds to a shear strain at failure of about 200%, whereas the best results obtained here correspond to 300%. The laminates are therefore capable of accepting shear strains well in excess of those encountered in bridge bearings, and may well be of use in high-strain applications such as earthquake mounts. The reservations about the coarse weave of the Aramid fabric resulting in a large flaw size were not borne out by these results. Both glass and Aramid fabrics gave essentially the same relationship between peel load and shear stress, suggesting that the weave of the fabric was not of great importance in determining the failure stress.

Failure Criteria for Laminated Bearings

The limiting factors determining the suitability of a material in a rubber mount are its stiffness and strength. Although it is possible to predict properties such as bending stiffnesses of reinforcing layers from standard elasticity equations, analysis of the stresses exerted by a rubber on a reinforcing layer has not received much attention. Compression of a laminated mount results in a tensile stress being exerted on the rigid layer. The magnitude of this stress is a limiting factor in determining the suitability of a material for use in such an application.

The shear stress exerted on a bonded rubber disc at a radial distance from the centre is given by[8]:

$$\tau_{xy} = Ere/h \qquad \ldots 1$$

where E is Young's modulus, e the compressive strain and h the thickness of rubber. The shear stress can to a first approximation be treated as a body force *(R)* acting on the rigid disc of thickness *t*, so that

$$R = Ere/th \quad \ldots 2$$

The stress acting on the rigid disc can be derived by analogy with a rotating disc for which the solution is known[9], so that the peak radial (σ_r) and hoop (σ_Θ) stresses at the centre of the disc are

$$\sigma_r = \sigma_\Theta = (3 + \upsilon).\ Eher^2/8th^2 \quad \ldots 3$$

where υ is Poisson's ratio.

As $r/2h = S$ = shape factor = one loaded area/total force free area

$$\sigma_r = \sigma_\Theta = (3 + \upsilon).\ EhS^2.\ e/2t \quad \ldots 4$$

If the rubber disc has a high shape factor the compressive stress σ_c will be

$$\sigma_c = 2ES^2e \quad \ldots 5$$

The peak stress on the reinforcing layer is related to the compressive stress by

$$\sigma_r = \sigma_\Theta = (3 + \upsilon).\ h\sigma_c/4t \quad \ldots 6$$

This relationship shows that the peak stress causing yield or fracture of the rigid layer is *related only to the relative thickness of rubber* and reinforcing layer and the yield or tensile strength of the reinforcing layer.

The above relationship was derived assuming the reinforcing layer was an outer layer. For internal layers the peak stress exerted by the rubber will be twice as great. Therefore the failure stress (σ_f) for an internal layer should be given by

$$\sigma_f = 2tT/h(3 + \upsilon) \quad \ldots 7$$

Taking $\upsilon = 0.4$

$$\sigma_f = 0.59tT/h \quad \ldots 8$$

where T is the peak stress at failure and is equal to the tensile strength or yield stress of the reinforcing material.

According to this analysis, the centre of the layer is in equi-biaxial tension; strength data are not available for this type of deformation. Since tensile strength data are available for most materials, this measure of strength has been used to obtain the value of tT. In the case of fabrics, the quantity tT is the tensile strength per unit width, taken as 1.5×10^5N per metre for glass fabric and 3.35×10^5 N per metre for Aramid fabric. The value of T for glass-reinforced Nylon 66 was taken as 150 MPa, while the yield stress of Nylon 66 was taken as 50 MPa.

The relationship between the quantity 0.59 T/h and the observed failure stresses for various laminates is shown in *Figure 8*. The failure stress values were obtained by compressing the laminates at 2 mm per minute until fracture of the reinforcing layer occurred, accompanied by an audible sound. For the fabrics, failure resulted in a single tear through the fabric, while the reinforced nylon was shattered.

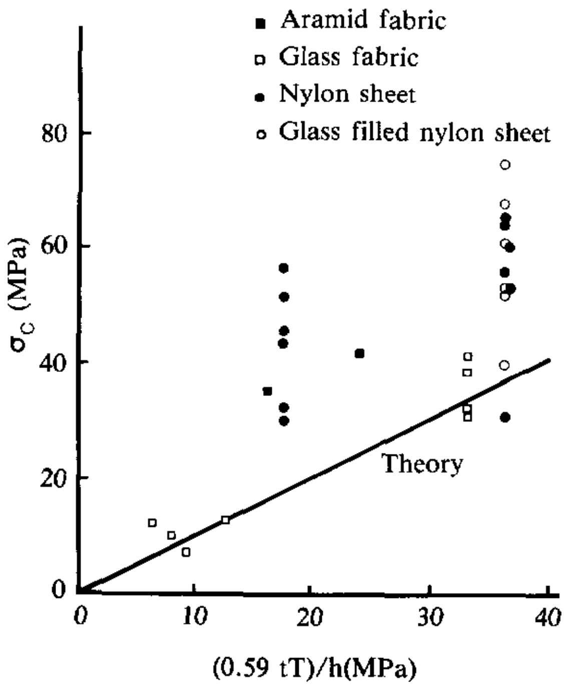

Figure 8. Comparison of compressive stresses at failure with the predicted values, for fabric reinforced NR bearings.

Agreement with the analysis was not good *(Figure 8)*, the tensile strength tending to underestimate the ultimate strength of the laminates. Only unreinforced nylon sheet, which is ductile, gave good agreement. Nevertheless the relationship gives a good indication of the lower limit for the achievable compressive loads, and enables acceptable loads to be predicted from readily available strength data.

The data shown in *Table 2* confirm that the compressive stress at failure is determined by the thickness of the rubber layer and not by the plan dimensions.

Using this relationship and permitting only two-thirds of the predicted failure stress as a margin of safety, the permissible stresses calculated for laminates having 10 mm-thick rubber sections are shown in *Table 3*. In practice, the laminates based on fabrics and filled nylon would normally withstand stresses at least three times higher than the figures shown in *Table 2;* all the large laminates have been proof-tested to 15 MPa.

TABLE 2. EFFECT OF RUBBER THICKNESS AND PLAN DIMENSIONS ON ULTIMATE STRESSES

Rubber layer thickness (mm)	Approximate dimensions (mm)	Failure stress (MPa)
Glass fabric laminates		
5.5	13 × 26	56
	25 × 25	51
	25 × 50	43
	25 × 75	45
	75 × 75	32
	100 × 100	30
2.5	12 × 14	65
	14 × 27	60
	26 × 24	64
	26 × 50	60
	75 × 75	55
	102 × 102	52
Aramid (Kevlar 7550 laminates		
5.45	27 × 27	39
	50 × 50	51
	79 × 78	52
	101 × 101	67
	129 × 129	60

It is interesting to note here that the NR/glass or Aramid laminates are considerably stronger than commercial chloroprene rubber/glass laminates. The mean failure load of the latter was reported to be 10.7 MPa, while the 12 MPa obtained here was the lower limit observed, the mean value being approximately twice as high. This was achieved with a single fabric layer, whereas chloroprene rubber laminates use double layers of glass in internal reinforcing layers. The higher compressive strengths of these NR/laminated bearings is important in view of the proposed increase of permissible loadings from 5.5 - 6.9 MPa by California Department of Transportation.

Stiffness of Model Bearing

According to theory[10], the compression stress exerted by a bonded rubber block is given by

$$\sigma_c = 3G\,(1+2s^2).e \qquad \ldots 9$$

where G is the shear modulus and e the compressive strain. When the compressive strains are larger than a few percent, this relationship needs to be modified to

$$\sigma_c = G\,(1+2s^2)\,(\lambda-\lambda^{-2}) \qquad \ldots 10$$

where λ is the extension ratio $(1 - e)$. If the surface to which the rubber is bonded is essentially inextensible, the shear modulus obtained from

$$G = \sigma_c/(1+2s^2)\,(\lambda-\lambda^{-2}) \qquad \ldots 11$$

should be the same as that of the rubber in homogeneous compression.

The measured moduli have been compared at equivalent shear strains. The results are shown in *Figure 9* where the points represent moduli derived from compression of laminates,

TABLE 3. CALCULATED PERMISSIBLE STRESSES

Laminate	Laminate weight/ unit area or thickness	Calculated permissible stress (MPa)
Glass fabric	850 g/m^2	6
Aramid fabric	220 g/m^2	6
Aramid fabric	500 g/m^2	13
Unfilled nylon sheet	3 mm	7
Glass-filled nylon sheet	3 mm	20

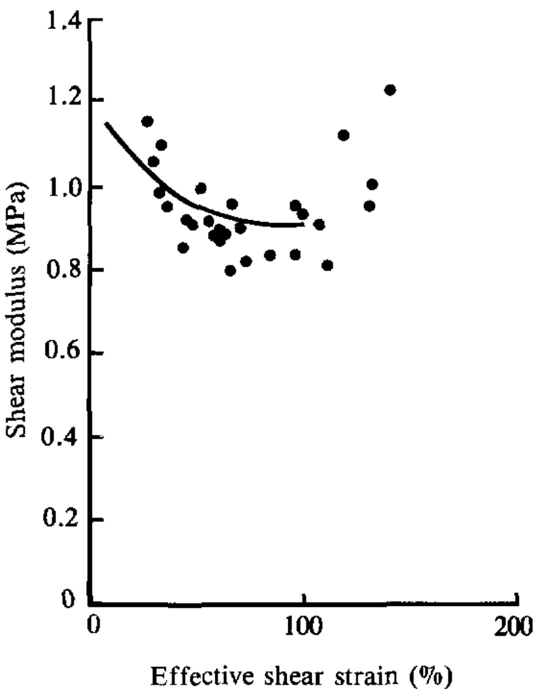

Figure 9. Shear moduli calculated from compression of glass/rubber laminates. The solid line shows the experimental values for the rubber in homogenous compression.

while the solid line corresponds to values calculated from homogenous compression of the rubber. Agreement between shear moduli calculated in this way is good, suggesting that for all practical purposes the glass fabric can be regarded as inextensible.

CONCLUSIONS

New approaches have been developed for the construction of laminated NR bearings in which steel plates are replaced with fabric and thermoplastic laminates, offering potential economies in raw materials and in fabrication.

Of the various materials tested, Aramid fabric appears best able to satisfy the requirements, judging from laboratory tests, including long-term exposure to water. The bonding system which produced the best results is Chemlok 402.

The theory developed does not accurately predict the failure loads for rubber laminates, but it does appear to give a reasonable prediction of the lower limits of failure stress.

ACKNOWLEDGEMENT

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