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SUMMARY

Two polyester sewing threads with different breaking strengths were used in the construction of sewn joints in four types of webbing. The joints were made having either a 3-point double W stitching pattern of various lengths or a number of rows of transverse stitching. The breaking strength of the stitched joints attained a limiting value. Various methods of seam strength prediction have been investigated.

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CONTENTS

1 INTRODUCTION

When joining fabrics by sewing, it is desirable to obtain the highest seam strength possible. A minimum seam efficiency (seam strength as a percentage of the original strength of the fabric) of 80% is quoted by Birch[1] as a design requirement, while Burtonwood and Chamberlain[2] state that it is difficult to obtain a seam efficiency greater than 85-90%. In addition to the actual damage to the fabric caused by sewing, e.g. needle bluntness, size of needle, speed of sewing and fusing of fibres as discussed by several authors[3-7], other factors need to be taken into account before sewing commences, e.g. the condition of the fabric and its ability to accommodate yarn movement as the sewing needle penetrates[8]. In relation to the end-use, some of the other points to be considered are the type of seam, length of overlap, stitching pattern, stitching frequency, fibre type and count of sewing thread.

Failure of seams in clothing, while being unsightly, may not lead to serious consequences. For some applications, e.g. parachutes, it is highly desirable to avoid failure. To ensure safety in operation seams may incorporate reinforcing tapes, or have long lengths of overlap, and penalties such as extra weight, increased stiffness and bulkiness may result.

The various parachute designs involve joining together in different combinations woven fabric, ribbons, tapes and cordages by stitching using a number of seam types and stitching patterns. The rigging lines may be long lengths of cordage that pass from the keeper over the canopy and back to the keeper, so that each length constitutes two lines. Other designs use shorter lengths attached at the canopy hem; these may be doubled through hem loops and the ends held by zig-zag stitching. In yet other versions the lines may extend a short distance up the canopy or they may go as far as the apex. The lines may be free to move through a fabric tunnel or may be held in seams with stitching along the length of the line and sometimes, in addition, held in position with stitches perpendicular to the longer axis of the line. The seams vary from a simple lap joint to more complicated structures in which one of the fabrics may be doubled with other layers inserted between the folds. In ribbon parachutes, the horizontal ribbons that form the canopy are stitched to radial and vertical ribbons.

In operation, the rigging line is tensioned along its length, i.e. mainly in one direction, whilst the material attached to it by sewing can be loaded in other directions but principally 90°.* Swallow and Fox[3], using a mock-leno nylon

*Tansley designed a rig[9] to simulate the loading where the rigging line was sewn to the periphery of the parachute canopy and a given percentage of the load applied to the line could be transferred to the periphery.

fabric, made samples having crossed seams at right angles to one another. These seams were tested on a bursting test apparatus so that all threads were loaded. In the present study of sewn joints a simplified version of this effect was used because of the difficulties in loading test pieces orthotropically. A short length of webbing was sewn to a longer length which could be tensioned and this structure is referred to as a superimposed joint (Fig.1a); Ferrier[10] used this configuration in some of his work. The sideways loading is omitted but part of the restraint due to sewing is present. The other type of seam studied was a lap joint (Fig.1b) which is frequently used in parachute construction. A sewing pattern used extensively when making parachutes and specified for testing heavy-weight sewing threads[11] is the double W (Fig.1c). This was used for making the superimposed and some of the lap joints. Other lap joints were made with rows of transverse stitching.

In the work described in this Report, some aspects of a few of the points mentioned above were studied. Two polyester sewing threads were used to make sewn joints in four types of webbing. The joints were tensile tested and three main types of failure occurred: the sewing thread broke, the webbing tore at the beginning of the seam or the sewing thread and webbing both failed. This last mode of failure was not so common, however.

2 MATERIALS

2.1 Sewing threads

The majority of seams were made using a 3-ply polyester sewing thread having a single to fold designation[12] 28 nominal tex f47S679 × 3Z464; R88.6 tex. A 2-ply polyester thread with single to fold designation 28 nominal tex f47S682 × 2Z532; R57.9 tex was also used. The twist is given in turns/m[13].

2.2 Webbings

Details of the webbings* are given in Table 1. The four webbings, made from different types of fibre, were circularly woven with nominally the same width and thickness. Webbings G and F were woven under a Ministry of Technology contract to have a construction similar to that of webbing D, a standard parachute material. Webbing J, woven to a firm's specification, had a circular twill weave and was slightly thicker than the other webbings. Further details regarding the stress/strain behaviour of these webbings have been reported by Stagg[14,15].

*The webbing reference letters used in this Report were assigned to three of the webbings (G, D and F) when their shrinkage in the presence of moisture was studied. This work will be reported later.

3 JOINT CONSTRUCTION

3.1 Sewing machine

The sewn joints were made with a Singer lockstitch hand sewing machine fitted with a Simanco size 16 needle. For most of the sewing the stitch length setting used gave an average of 3.7 stitches per cm of stitched length for two layers of webbing when sewn together in a 3-point double W pattern (Fig.1c) along the length of the webbing. This stitch length setting was altered when sewing the transverse rows (see section 3.4).

3.2 Superimposed and lap joints, 3-ply sewing thread, 3-point double W

The superimposed seam (Fig.1a) had a short piece of webbing sewn over the central area of a longer length of the same webbing. To test this joint the ends of this longer length were held in the jaws of the tensile testing machine and the ends of the shorter webbing were free. The lap joint, seam type LSa-1 [16], is illustrated in Fig.1b.

A 3-point double W (Fig.1c), 10mm wide, with the points equally spaced, was stitched along the length of webbings. The length of sewn overlap was in accordance with the test programme given in Table 2, and the short free end of the webbing extended 20mm beyond the end of the sewing, to avoid yarns pulling through prematurely when the webbings were tested. After construction, the sewn joints were placed in a conditioned room (20°C, 65% RH) until required for testing.

3.3 Lap joints, 2-ply sewing thread, 3-point double W

A small number of lap joints were made using webbing G and the 2-ply polyester thread in a 3-point double W stitching pattern. The lengths of sewn overlap were 20, 30, 40, 60, 80 and 120 mm. These samples were conditioned prior to testing.

3.4 Lap joints, 2- and 3-ply sewing threads, various stitching patterns

3.4.1 Lap joints with transverse rows of stitching

Webbing G was used for making lap joints having between 1 and 12 transverse rows of stitching equally spaced 15mm apart. Sets were made for each sewing thread. As the previous stitch length setting resulted in about five stitches across the width of the webbing, the stitch length was shortened to give seven stitches per row, equivalent to 4.8 stitches per cm. This shorter stitch length was below the optimum length (5.6 stitches per cm) quoted by Swallow and Fox[3] for a 3-ply polyester sewing thread of approximately the same count. The longer stitch length (3.7 stitches per cm) mentioned in section 3.2 was at the lower limit of the range between which they found that stitch length was not critical. In work on seams where failure was due to fabric breakage, Burtonwood and Chamberlain[17] found that maximum seam strength was attained using 5.6 stitches per cm. They used two sizes of needle and with the larger size (number 14) concluded that increasing needle damage caused a weakening of the fabric at stitch rates greater than 7.2 stitches per cm.

For all joints, the threads were tied together with a reef knot at each end of a row of stitching so that the knot was close to the surface of the webbing in order to prevent the free ends pulling through.

3.4.2 Stitching patterns with the same number of stitches

Another group of lap joints with webbing G was constructed with the 2- and 3-ply sewing threads used in different stitching patterns having approximately the same number of stitches. These patterns are illustrated diagrammatically in Fig.2. This number of stitches, 40, was based on five transverse rows of stitching. The two knotted stitches at the ends of a row were counted as one stitch and added to the number of regular stitches (see Table 3).

3.4.3 Combination of sewing threads, transverse rows

Lap joints were also made with webbing G having a combination of the two sewing threads in rows of transverse stitching. The threads were sewn as follows:

Total number of rows	Order of sewing*
3	2 3 2
3	3 2 3
4	2 3 3 2
4	3 2 2 3
4	3 2 3 2
5	3 3 2 3 3
5	2 2 3 2 2
5	3 2 3 2 3
5	2 3 2 3 2
5	2 3 3 3 2
5	3 2 2 2 3
9	3 3 3 2 2 2 3 3 3
9	2 2 2 3 3 3 2 2 2

*2 = 2-ply thread
3 = 3-ply thread

This was done to determine whether the sequence in which the rows were sewn would influence the results.

4 TESTING OF SEWING THREADS AND SEWN JOINTS

4.1 Testing of sewing threads

Tensile tests on the two sewing threads were performed on a Scott Inclined Plane Testing Machine under standard textile testing conditions (20°C, 65% RH).

In lockstitch sewing, the stitches are formed by the intersection of two loops of thread which, in a well-made seam, should lie between the two layers of fabric being joined. A method for the determination of the loop strength of yarns is given in B.S. Handbook 11 [18]. In loop tests on the two polyester threads, a length of thread was passed through a loop in another piece of the same type of thread, the ends clamped in the jaws of the testing machine, and the sample broken. In a sewn joint, however, the places where the sewing threads enter or leave the fabric are not equidistant from the loop when the seam is tensioned and unequal movement of the threads results in the angle between the sewing thread and the direction of loading being very different from that in a loop strength test.

For knot tests[18], a thumb-knot such as that used by Burtonwood and Chamberlain[2] was tied in lengths of thread and these samples were broken on the Scott Tester. It was assumed that the strength of this type of knot would not differ appreciably from that of the reef knots used to secure the seam ends, as described above.

To assess any loss of strength in the sewing threads themselves due to the action of sewing, two layers of Whatman number 1 filter paper were sewn together with the 3-ply polyester thread using the same stitch length that had been used in sewing the longitudinal seams. With paper this setting gave 3.2 to 3.3 stitches per cm. When a sufficient length had been sewn, the paper was torn away, the threads separated and conditioned at 20°C and 65% RH, and the needle and bobbin threads tested for tensile, loop and knot strength.

4.2 Testing of sewn joints

The joint strength for many of the sewn joints (using the 3-ply sewing thread) was beyond the maximum load of a Denison textile testing machine situated in a conditioned room (20°C, 65% RH). For the group of joints mentioned in section 3.2, about half of the samples were tested on an Avery machine in an unconditioned laboratory, jaw breaks being eliminated by use of the jaws described by Stagg[14]. Wave profile jaws, packed with rubber-coated fabric, were used on the Denison machine when testing the remainder of the joints mentioned in section 3.2 and the lap joints (section 3.3).

While the work was in progress, a Monsanto Tensometer E testing machine was installed in the conditioned room. The joints described in section 3.4, i.e. those with different stitching patterns, lap joints with between 1 and 12 transverse equally-spaced rows and those sewn with the combination of two sizes of thread were all tested on this machine using the jaws that had been used on the Avery.

5 RESULTS

5.1 3-ply sewing thread

Results for tex, breaking strength, tenacity and extension for the 3-ply polyester thread (original unsewn, and unpicked needle and bobbin threads sewn into filter paper) are given in Table 3a. The two sewn threads were slightly crimped and about equal in length for a given distance sewn. The increased count of the sewn threads from the original thread is probably due to the crimping produced by sewing and the 6-8% reduction in breaking strength indicates that some damage due to sewing has occurred.

Also given in Table 3a are the 99% confidence limits of the mean for tex, breaking strength and tenacity for the original and sewn threads as calculated from the relationship[19]:

$$\bar{y} \pm t\left[(\hat{\text{var}}\ y)/n\right]^{\frac{1}{2}}$$

where $\bar{y}$ = mean of results,

$\hat{\text{var}}\ y$ = best estimate of the variance of y ,

n = number of results

and t = students 't' ,

using the value of 't' for the required level of probability with $(n - 1)$ degrees of freedom.

At a given level of probability, the apparent difference between the means for two sets of results containing n_1 and n_2 results, respectively, can be checked by calculating the related 't' value[19] and comparing it with that given in tables for $(n_1 + n_2 - 2)$ degrees of freedom. The calculated 't' values in Table 4 show that there is a significant difference in means at the

99% probability level between the original and sewn threads for tex, breaking strength and tenacity. The reduction in tenacity due to sewing is approximately 13% and about 7% of this reduction is due to the increased count. It would appear, therefore, that sewing has a damaging effect on the thread. Crow and Chamberlain[4] also found that the thread strength was reduced on sewing and for continuous filament threads sewn at different speeds they found a 13-17% reduction in tenacity. A difference is established at the 95% probability level for count, breaking strength and tenacity between the sewn needle and sewn bobbin threads. On the sewing machine used the alteration in properties, except for breaking extension and knot strength, was significantly different at the 95% probability level between the upper needle thread and that supplied from the bobbin. The latter thread has the higher breaking strength and tenacity.

The extension is approximately the same for all three conditions of the thread.

The results for the loop and knot strengths for the 3-ply polyester thread are given in Table 3a with the 99% confidence limits for the mean; in B.S. Handbook 11 [18] it states that the mean of the breaking load readings for the loop strength shall be quoted, and this is the value given in Table 3a. Under 'Remarks' in the B.S. Handbook it mentions a 'loop strength ratio': the ratio of the loop strength to twice the single-thread strength for 7in specimens. The loop strength ratio for the 2-ply thread is 0.74 and for the 3-ply 0.68. Similarly, Skelton[20] using loop efficiency [(loop strength/2)/breaking load] × 100, found that the loop strength ratio decreased as the yarn diameter increased but he was not sure why this occurred.

Brain[21] found "knot strengths to be up to 30% weaker than loop strengths". On the limited number of tests done in the present work, it has also been found that knot strengths are usually 20 to 30% lower than halved loop strengths. The values reported here for mean knot strength are just over 56% of the mean tensile strength. Borwick[22], concerned with the strength of climbing ropes, gave results for a variety of knots tied in ropes. With a reef knot, the rope retained 50% of the unknotted strength and he stated that the figure would vary for different makes and sizes of rope. A thumb knot will probably retain about the same percentage of the unknotted strength as a reef knot, but the great difference in construction between rope and sewing thread makes comparisons difficult.

A difference in means was not established between results on the original loop and those on loop strength for sewn needle threads; it is however at the

95% level between original and sewn loop strength for the bobbin thread and between sewn needle and sewn bobbin (Table 4). For the tensile strength results it was established that there was a highly significant difference between the original and sewn threads and at 95% probability level between the two sewn threads. The differences between the mean knot strengths are not significant for the original and sewn conditions. It would appear that the damage due to sewing is not so great as that in the loop test and that the action of the knot is very severe and submerges any alteration in properties due to sewing.

5.2 2-ply sewing thread

The results for the 2-ply sewing thread are given in Table 3b and it can be seen that the 2- and 3-ply threads do not differ significantly in tenacity. The 99% limits for the knot strength of the 2-ply thread are between 54% and 65% of the original tensile strength, which is in reasonable agreement with the percentage obtained for the 3-ply thread.

5.3 Superimposed and lap joints, 3-ply sewing thread, 3-point double W

At break the stitching ruptured completely for 21 of the 40 lap joints but this did not occur for any of the superimposed joints. For the remaining samples part of the stitching broke and then the webbing failed near one end of the stitched length. With the shorter stitched lengths it was not easy to judge how the stitching parted but failure probably started at the ends. Mitchell[23], in measuring the strain in stitched joints, considered that the end stitches were likely to fail first and Jackson[24] thought that joint efficiency was dependent on the high local loads in the end stitches of joints. On the longer lengths of overlap, the stitches could be seen breaking at each end of the double W at approximately the same rate and eventually the webbing broke at one end of the stitching, often with a tail running along one of the lines of stitching. Webbing F suffered weft breakage at points where the stitching pulled and the break, with no tail, usually occurred right at the beginning of the stitching.

The breaking strength results for these two types of sewn joint are plotted in Figs.3 and 4, and stitching failures are indicated by circles round the symbols. With webbings G and F the plotted lines obtained for the two types of sewn joint tend to coincide at a discontinuity in the lap joint graph, where joint failure due to complete stitching breakage transfers to a mixture of some stitches breaking and tearing of the webbing. This point occurs at about 60mm length of sewn overlap for webbing G and at 80 mm for webbing F. Analysis of variance was performed using the results for these two webbings (Table 5). Comparison of the two types of joint with between 80 and 400 mm of sewn overlap showed that type of joint, length of overlap (between 80 and 400 mm) and their interaction were not significant, whilst the effect of webbing was significant at the 99.9% probability level. The superimposed joints had a high initial strength which fell with increasing length of overlap. This decrease was rapid at first and then slowed until it reached a similar strength level to that obtained for the lap joint in the same webbing.

The difference required between pairs of means to achieve significance at a given probability level were calculated as follows:

$$p - q = t\left[(2KM)/N\right]^{\frac{1}{2}} \quad \text{with} \quad 2\left[(N/M) - 1\right] \quad \text{degrees of freedom}$$

where p and q are the means to be compared,

K = residual variance,

M = number of levels,

N = total number of tests

and t = students 't' at a given probability level.

The differences for significance at the 99.9% probability level for the main effects are given in Table 6. Webbing type was significant but the differences between means for joint type and length of overlap were small.

The strength of the lap joint rises with increasing length of overlap and initially the results for the four webbings were approximately on the same line. Analysis of breaking strength variance for the lap joints with stitching failure indicated that the webbing effect was not significant (Table 7). The analysis was split into two groups as there were only three lengths of overlap which could be used for the four webbings (Table 7a); by omitting the G lap joints, however, more levels for length of overlap could be included (Table 7c). For the different webbings, a difference between the breaking strength means of 0.39 was required for the first group (Table 7b) and 0.65 for the second (Table 7d) to achieve significance at the 99% probability level. These values were not reached by any pair of webbings in either of the groups. The effect of length of overlap was significant at the 99.9% level of probability for both groups.

The seam strength for webbing G reached a maximum and approximately the same value was obtained for 60 to 400 mm sewn overlap (Fig.3). The lap joints for the other three webbings increased in strength, at approximately the same rate though with some perturbations, until webbing F reached its maximum and, like webbing G, followed a line parallel to the overlap axis. The other two webbings continued to increase in strength, though the rate of increase was not so great and at the limit of sewn length studied (400 mm) webbing J could have been near to its maximum lap joint strength.

Assuming that the error variance of the stitching failures was comparable with that of the webbing failures, an analysis of variance, based on the factor levels in Table 2 and including zero strength at zero overlap, was performed and the results are presented in Table 8. The main effects and most of their interactions were significant at the 99.9% level of probability, and joint construction and webbing type had the highest variance ratios. The effect of length of sewn overlap did not depend on the webbing type.

The mean breaking strengths for the main effects and the significant interactions are given in Table 9; also given are the differences required between pairs of means to achieve significance at the 99% level of probability. The mean webbing joint strengths, averaged over both joints, are in the same ranking order as those for the original webbings. Differences between the means are signficant for most pairs, except D and F. For all webbings the superimposed joint was stronger overall than the lap, the greatest difference in strength being with J. For the lap joints in the webbing type/joint interaction, G was significantly different from the other webbings, and these did not differ much among themselves. For the superimposed joints in this interaction, all webbings were significantly different from each other; the greatest difference between means was for G and F and least between F and D.

The overall strength of the lap joints reached a limiting value with increase in length of sewn overlap. Differences between pairs of means for length of overlap, when this was considered as a main effect, were not significant between adjacent pairs when the results were ranked in order of strength. Significant differences were only obtained for lengths of overlap between 10 and 80 mm when the pairs had two other results in between. This lack of significance between means for a highly significant main effect may be due to the discontinuous curve for the lap joints and the assumption that the errors, while being randomly and normally distributed, follow the same pattern for both parts of the curve. For the interaction of length of overlap with type of joint, significant differences between the means were obtained for lap joints between every other pair from 0-60 mm overlap and from 0.80 mm with two results between each pair. For lap joints with longer lengths of overlap there were no significant differences. With the superimposed joints there was no significant difference between any pair of means, except that all the results were significantly different from zero overlap.

Thus, the maximum lap joint strength obtainable for a given webbing is dependent on the strength of the original unstitched webbing and there would appear to be, for a given sewing thread and stitching pattern, an optimum sewn length of overlap. For the webbings studied, this length would appear to be about 80 mm for webbings G and F and possibly longer for D and J. Longer lengths of overlap than this, requiring additional webbing, will only increase the cost and bulk of the joint without conferring the benefit of increased strength.

The seam efficiencies are given in Table 10. Webbing G does not reach 80% seam efficiency, and, of the others, J would appear to be only just able to maintain this level under the conditions studied.

5.4 Lap joints, 2-ply sewing thread, 3-point double W

The results for lap joints made in webbing G using the 2-ply sewing thread in a 3-point double W sewing pattern (see section 3.3) are plotted on Fig.3.

As with the lap joints made with the 3-ply thread the strength at first rises with increasing length of sewing and then levels out at about 60 mm sewn overlap. The shape of the two curves for lap joints in webbing G with 3- and 2-ply sewing thread is similar with the 2-ply curve displaced to the right of the 3-ply. The initial slopes (based on stitching failure) are not significantly different. The maximum joint strength would seem to be governed by the behaviour of the sewn webbing which is the same for both sewing threads.

5.5 Lap joints, 2- and 3-ply sewing threads, various stitching patterns

5.5.1 Lap joints with transverse rows of stitching

The results for the lap joints sewn with a number of transverse rows (section 3.4) are plotted in Fig.5. Each point represents the mean of five tests. An approximately straight line is obtained for both sewing threads up to six rows of stitching. The increase in seam strength then gradually rises for additional rows and apparently reaches a maximum at eight rows with the 3-ply thread and at ten for the 2-ply. For the 3-ply thread this value is about the same as that obtained, 2.5 kN, with 40-400 mm sewn overlap with a 3-point double W sewing pattern. As noted in section 5.3, this gives a seam efficiency of 68%.

The maximum breaking strength, 1.7 kN, given by ten transverse rows with the 2-ply thread gives a seam efficiency of 47% but this does not reach the maximum obtained with the double W pattern because only stitching failure occurred.

With nine and ten transverse rows of 3-ply thread, the webbing broke on some samples. For the same seam strength obtained with a double W, the webbing broke when the sewn overlap was 40 mm or more: the joint strength was then a combination of thread and webbing strengths. With the 2-ply thread and transverse rows, only stitching failures occurred.

5.5.2 Stitching patterns with the same number of stitches

The seam strengths for the different stitching patterns, each having the same number of stitches (40), are given in Table 11 together with the associated variances and the 99% confidence limits. For five transverse rows the value is the mean of five results and for the other patterns the mean of three tests. With the 3-ply sewing thread the mean breaking strengths for the longitudinal and single W patterns are significantly different at the 99% probability level from that for five transverse rows, whilst the zig-zag is not. The transverse and zig-zag patterns have similar ranges which are overlapped by the more variable single W. This latter pattern is also the most variable when sewn in the 2-ply thread and again the ranges for five transverse rows and zig-zag are comparable. For all patterns using the 2-ply thread there is no significant difference between the mean breaking strengths. If these 40 stitches in the 3-ply thread were arranged in a 3-point double W this would occupy approximately 17mm sewn overlap and, from Fig.3 for webbing G lap joints, this length of overlap corresponds to a seam strength of about 1.7 kN.

Northey[25] found that 15 stitches in three equally-spaced transverse rows across the width of nylon webbing gave a higher seam strength than 16 stitches in four parallel rows sewn longitudinally along the webbing. This finding supports the present results for the 3-ply thread: for a given number of stitches in transverse rows a higher strength is obtained than for the same number of stitches sewn along the length of the webbing, although the deployment of the stitches is different from that of Northey in the longitudinal direction. For the 2-ply thread the two patterns give the same values.

Burtonwood and Chamberlain[2] found that, for equal numbers of stitches, rows of stitching perpendicular to the direction of loading gave a higher seam strength than rows parallel to the direction of stress. They considered that the strength of a seam made with a 4-point double W stitching pattern would be close to that given by the transverse rows but did not test actual seams. Timby[26] in sewing tests on a standard nylon webbing found that a nylon thread in a 4-point double W stitching pattern was approximately equal in strength, for the same number of stitches, to that of a diamond pattern worked horizontally along the webbing. With a flax thread on the same nylon webbing he found that the strength of the double W decreased, after passing a maximum (which was considerably lower than that for the nylon thread), in comparison with other patterns having the same number of stitches. He said this was due to the rows of stitching being too close together, with consequent deformation and cutting of the stitches and webbing.

Ferrier[10] constructed hem joints with a 3-point double W pattern stitched along the length of the rigging line, starting either at the canopy hem and going up the canopy or with the sewing at right angles to this direction over the intersection of the line with the hem reinforcement. The maximum joint efficiency for both these two types was 90%. An increase to 93% joint efficiency was obtained by sewing two parallel double W patterns, 76mm long, along the hem reinforcement and on the first ribbon where these were covered by the rigging line. In dynamic tests on these joints[27], the efficiencies were 77% for stitching along the line and 79% for two parallel double W patterns along the hem.

5.5.3 Combination of sewing threads, transverse rows

The results for breaking strength of sewn lap joints made with a combination of both sewing threads, taking the mean of five tests for each type, are given in Table 12. As would be expected, combinations containing the greater number of 3-ply rows had a higher breaking strength for a given group. There was a tendency for the higher breaking strengths to occur when the 3-ply rows were grouped together (compare 23332 with 32323) or constituted the outer rows (32223 compared with 23232). As failure took place so rapidly it was not easy to judge which rows of stitching failed first, but all were stitching breaks. On the few occasions when it was possible to see what happened, one or more of the 2-ply rows broke before the 3-ply; this was noted when the 2-ply rows were the outer rows and when they were near the centre. All combinations, except one, gave strengths intermediate between those for the corresponding number of all 3-ply or all 2-ply rows. In only one case, 22322, was the value approximately equal to that of five 2-ply rows.

6 PREDICTION OF SEAM STRENGTH

6.1 Published methods of prediction

In section 5, it was found that in those seams where seam failure was due to thread breakage, there was an approximately linear relationship between increasing seam strength and (a) length of sewn overlap, or (b) number of transverse rows of stitching. When the mode of failure changed to tearing of the webbing, the resulting plot was curved and approached a limiting seam strength for a given webbing.

Burtonwood and Chamberlain[2] made seams in cotton twill fabric with an increasing number of rows of transverse stitching so that all seams failed by thread breakage. Their plot of seam strength against rows of stitching was approximately linear for up to four rows and in reasonable agreement with their prediction based on minimum knot strength. After this the results were lower than predicted and the curve became non-linear.

Brain[21] measured various thread strength properties which enabled him to obtain a function for thread strength and derive a formula for predicting seam strength for some of the combinations of sewing threads and fabrics studied. The best prediction was obtained using a function he referred to as the "corrected minimum loop strength of the sewing thread", in which the angle made between the arms of the thread loop when loaded was considered to modify the minimum loop strength. No universal formula was obtained to fit all the threads and fabrics tested.

Howarth[6] considered that seam strength was related to the loop strength of the sewing thread and the stitch rate for small numbers of stitches per cm. Only with the heaviest fabric examined, however, did the different thread counts have a noticeable effect.

Ferrier[10] used a superimposed joint as one of a number of variations studied in an assessment of strength loss as a parachute hem joint was built up. The comparable joints had a 3-point double W either 150 mm or 50 mm long sewn in two layers of 14.7 kN nylon webbing (22 mm wide) and he obtained joint efficiencies of 80 and 96%, respectively. In a variation of this joint type, instead of having two pieces of the same webbing Ferrier used four layers of a radial ribbon for the shorter, superimposed length. This had a joint efficiency of 83% for a 150 mm sewn length with a 3-point double W. He concluded that the difference in joint efficiency was related to the longitudinal stiffness of the materials (two layers of webbing versus one layer of webbing combined with ribbons).

6.2 Methods of prediction based on reported results

The interaction of the thread with the webbing type and structure of the fabric into which it is sewn, frictional effects and tightening of the weave under load are some of the factors which make seam strength predictions difficult. With additional rows of stitching the yarns may be displaced and the same group of warp threads may not be held by the corresponding stitch in every row.

In section 5.1 it was found that the sewing thread was weakened while being sewn and in section 5.3 it was established that there was a maximum joint strength obtainable. Having reached this limit there appeared to be no advantage in increasing the length of sewn overlap as this possibly resulted in unnecessary weakening of the webbing. The basic structure of the webbing and fibre type govern the ultimate strength of the construction, and the resulting seam efficiency depends on this and other factors such as type of seam and sewing thread.

In an attempt to predict seam strength where seam failure was due to thread breakage, calculations were made for the 3-ply sewing thread using an increasing number of transverse rows (up to six, as up to this point the curve was linear, see Fig.5), number of stitches (7/row and 7 + 2 knotted stitches/row), and original tensile, sewn needle tensile, loop and knot strengths. The predicted seam strengths are given in Table 13a and the differences between actual and predicted are plotted in Fig.6. The smallest differences were given by original tensile strength in comparison with actual seams. Sewn needle plus sewn knots also gave reasonable agreement. The thread properties giving the best predictions (columns 3, 4, 5, 6 and 9, Table 13a) and the actual results were combined in an analysis of variance (Table 14). The increasing numbers of rows of stitching gave a very high variance ratio for the row effect and the thread property was also significant at the 99% probability level. The means for each thread property, Table 15, show that the original tensile strength is closest to that of actual seams. The difference required between means at the 99% probability is 0.14 and is given, in two cases, by every other pair when the results are ranked in order of breaking strength. Significant differences are obtained between (original + knots) and actual, and between original tensile and (sewn needle loop/2 + knots).

Calculations using loop strength gave values which were higher, the difference increasing rapidly with the greater number of rows (Fig.6). In a loop test the loops are approximately in line with one another, whilst in a seam under tension the stitch loops are displaced at an angle due to the thickness of the webbing. Additionally, in a seam the loops are affected by the behaviour of the adjacent loops and those at the end of the row will be different because of the knots. Differences obtained using loop strength/2 gave a curve similar in shape to that for knot strength but with smaller differences from the actual seam strength. The inclusion of two knotted stitches/row with sewn loop/2 gave better agreement particularly up to four rows of stitching. The greatest differences from actual seam strength were given by knot strength.

The differences between predicted seam strength and actual values for the 2-ply thread are plotted in Fig.7. The differences using tensile strength were greater than those with 3-ply thread, which were approximately zero for rows 1-5, but similar differences were obtained using loop strength. Knot strength differences for the 2-ply thread were about half of those for the 3-ply. The best overall prediction for the 2-ply thread was given by loop strength/2 with 2 knotted stitches/row. This method was in reasonable agreement with actual seam results up to the eighth row.

It would seem that for certain combinations of thread and stitching pattern that loop strength/2 could be used instead of thread tensile strength for predicting seam strength, particularly for the 2-ply thread. This pointed to the possibility that loop strength multiplied by a factor might give a better prediction. A factor (R) was obtained as follows:

$$R = \frac{\text{actual seam strength} - (2 \text{ knotted stitches/row} \times \text{number of rows})}{\text{number of stitches/row} \times \text{number of rows} \times \text{loop strength of thread}} .$$

Values for R were 0.62 based on sewn needle thread values for the 3-ply (R_3) and 0.47 for the 2-ply thread (R_2). Seam strength predicted using R, loop strength, number of stitches and 2 knotted stitches/row gave good agreement with actual seam strengths and the differences are plotted in Fig.8. Overall, the differences for the 3-ply thread are slightly better than when original tensile strength was used for prediction and better than loop strength/2 plus knots for the 2-ply thread.

The angle θ, between the arms of the loop of sewing thread as it leaves the intersection with the other thread when making a stitch, varies with the count of the sewing thread. This angle is larger for finer threads as they are not displaced to the same extent as those with a larger diameter. If $R = \cos(\theta/2)$, then $\theta = 103^{o}$ for the 3-ply thread and 124^{o} for the 2-ply. It should be possible, though difficult, to test this by experimental observation. Brain[21] concluded that $\cos(\theta/2)$ for given conditions gave the best prediction but he used it in conjunction with minimum loop strength.

It would thus appear that (loop strength × R) plus 2 knotted stitches/row is adequate for predicting seam strength when seam failure is due to thread breakage.

In section 5.5.3 seams were made using different combinations of both sewing threads, and seam failure was due to thread breakage. Four methods of seam strength prediction have been used and the predicted values are given in Table 12. In method P1, seam strength equals (number of rows in 3-ply × average breaking strength for one transverse row in 3-ply) plus (number of rows in 2-ply × average breaking strength for one transverse row of 2-ply). For P2, the actual breaking strength for a given number of rows sewn in each thread were added together. Method P3 uses (loop strength of each sewing thread × R_3 or R_2 as appropriate × number of stitches) + 2 knotted stitches/row for each row in 3- and 2-ply thread. For these three methods, correspondence with the actual results was good for some groupings but outside the 99% confidence limits of the experimental means in four cases. For these seams made with a combination of the 2- and 3-ply sewing threads, the average breaking strength per row when plotted against the fraction of 3-ply thread in the combined seam (Fig.9) gave a curve below the calculated line based on the average strength of a one row seam in 2-ply and 3-ply thread (solid line, Fig.9). The latter strength was assumed for seams starting with one sewn in all 2-ply thread then passing through different proportions of 2- and 3-ply threads to a seam made entirely from 3-ply. For this method, P4, an approximate equation for the curve was:

$$z = \left[z_2 + (z_3 - z_2)x - ax(1 - x)\right] n$$

where z = total breaking strength,

z_3 , z_2 = breaking strengths per row for 3- and 2-ply sewing threads, respectively,

x = proportion of 3-ply thread in seam,

$1 - x$ = proportion of 2-ply thread in seam,

a = constant,

and n = number of row.

The value of a was found to be 0.072. Inclusion of the 2-ply thread caused an interactive weakening greater than that due to the lower strength of the 2-ply thread alone, probably because of premature breakage of the 2-ply. The load would then transfer to the remaining rows in 3-ply and if greater than these stitches could withstand the seam would fail.

The relationship between actual seam strength and prediction calculated[19] for the four methods were as follows:

$$\text{P1:}\quad y = 0.228 + 0.744x_{P1}\,,\quad r = 0.96\,;$$

$$\text{P2:}\quad y = 0.252 + 0.730x_{P2}\,,\quad r = 0.95\,;$$

$$\text{P3:}\quad y = 0.230 + 0.750x_{P3}\,,\quad r = 0.96\,;$$

$$\text{P4:}\quad y = 0.231 + 0.792x_{P4}\,,\quad r = 0.96\,;$$

r = correlation coefficient.

Thus, while methods P1, P2 and P3 gave high correlation between calculated values and experimental results, all the points when plotted came below the line which had a slope equal to unity for perfect prediction. These calculated lines had slopes of about 0.75, the interaction having been neglected. Method P4 apparently had a slightly higher slope. However, none of the slopes differed significantly from unity ($t = 1.6$ on 11 degrees of freedom for P2, the worst case), so that any apparent improvements in fit may be illusory with the amount of scatter in the experimental data.

For seams with transverse rows of stitching sewn with a single thread type, the simplest method of prediction would be P3 as this is based on loop strength of the sewing thread and initially does not require the construction of seams.

The loop strength × R_3 × number of stitches method of prediction was used for calculating seam strength for lap joints sewn with a 3-point double W in the 3-ply thread. The calculations were restricted to lengths of sewn overlap where thread failure occurred on testing seams made in the four types of webbing. The values are given in Table 16. Although R_3 was calculated for the polyester thread in webbing G, it gave reasonable predictions for the other webbing types sewn with the same thread. The best agreement was obtained for webbing F as the initial part of the curve was reasonably linear throughout until the limiting value for seam strength was reached and subsequently seam failure was not solely due to thread breakage. For webbings D and J, the lines although initially linear became curved while seam failure was still due to thread breakage (see Figs.3 and 4). For lap joints in the 2-ply, a reasonable prediction was again obtained, but the predicted values were slightly lower than the actual results except at 60mm overlap. On testing this latter seam there was not a complete stitching failure, and although most of the stitches were broken some tearing of the webbing also occurred. On this limited amount of work, it would seem likely that the thread loop strength × R is independent of the textile into which it is sewn.

7 CONCLUSIONS

(1) Two polyester sewing threads were used in the construction of superimposed and lap joints in four types of webbing.

(2) The sewn joints were made having either a 3-point double W stitching pattern of varying lengths or a number of rows of transverse stitching.

(3) For the 3-ply sewing thread a significant difference was found between original and sewn thread properties, and sewing gave a 12.5% reduction in tenacity.

(4) A maximum value was obtained for the breaking strength of the lap joints and, for a given webbing, added strength was not achieved by increasing the length of sewn overlap.

(5) The superimposed joints were stronger than the lap joints, but with increasing length of overlap the strength fell to approximately the maximum value obtained with the lap joint for the same webbing.

(6) With the webbings studied 80% seam efficiency was not obtained for webbing G and only just attained for webbing J; webbing F was slightly better and 92% seam efficiency was reached with webbing D lap joints.

(7) Analysis of variance showed that the type of joint and webbing were highly significant.

(8) With an increasing number of transverse rows of stitching and where seam failure was due to stitching breakage, the increase in seam strength was linear for both threads.

(9) Of the stitching patterns considered, the 3-point double W was the most efficient on the basis of overlap required for a given strength.

(10) The best seam strength prediction, when seam failure was due to thread breakage, was given by the loop strength of the sewing thread multiplied by the number of stitches and by a factor related to the angle subtended in the loop.

(11) This method of prediction could be improved for transverse and lap joint seams if the appropriate number of knotted stitches was included.

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Table 1

DETAILS OF WEBBINGS

Webbing reference	Cordage number[14]	Fibre type	Weave	Width, mm	Thickness, mm	Breaking strength[14], kN
G	11	acrylic	circular, plain	15	2.05	3.70
D	10	nylon 66	circular, plain	14.5	2.02	8.22
J	2	polyester	circular, 2/2 twill	15	2.95	9.99
F	12	aramid	circular, plain	14.5	1.98	7.23

Table 2

LEVELS OF FACTORS

Type of joint	lap superimposed
Length of sewn overlap, mm	10 20 40 60 80 120 160 240 320 400
Webbing	G D J F

Table 3a

RESULTS FOR THE 3-PLY POLYESTER SEWING THREAD

	Original*	Sewn* needle	Sewn* bobbin	Original* loop	Original* knot	Sewn** needle loop	Sewn** needle knot	Sewn** bobbin loop	Sewn** bobbin knot
Tex, g/km	88.60	95.30	94.35						
Vâriance	1.01	0.56	1.40						
99% confidence limits, upper	89.63	96.07	95.57						
lower	87.57	94.53	93.13						
Breaking strength, N	49.79	45.70	47.30	67.93	28.08	67.72	27.06	70.95	26.72
Vâriance	0.77	3.04	1.47	5.32	3.22	4.07	3.02	13.38	2.47
99% confidence limits, upper	50.69	47.49	48.55	70.30	29.92	69.86	28.90	74.83	28.38
lower	48.89	43.91	46.05	65.56	26.24	65.58	25.22	67.07	25.06
Tenacity, N/tex	0.562	0.480	0.501						
Vâriance	0.0001	0.0004	0.0002						
99% confidence limits, upper	0.573	0.500	0.516						
lower	0.551	0.460	0.486						
Breaking extension, cm/cm	0.14	0.14	0.15						
Vâriance	0.0001	0.0002	0.0001						
99% confidence limits, upper	0.15	0.16	0.16						
lower	0.13	0.13	0.14						

* Mean of 10 tests
** Mean of 8 tests

Table 3b

RESULTS FOR THE 2-PLY POLYESTER SEWING THREAD

	Original*	Original* loop	Original* knot
Tex, g/km	57.94		
Vâriance	0.20		
99% confidence limits, upper	58.40		
lower	57.48		
Breaking strength, N	32.42	47.90	19.25
Vâriance	2.64	1.69	0.58
99% confidence limits, upper	34.09	49.24	20.03
lower	30.75	46.56	18.47
Tenacity, N/tex	0.560		
Vâriance	0.001		
99% confidence limits, upper	0.591		
lower	0.528		
Breaking extension, cm/cm	0.11		
Vâriance	0.0003		
99% confidence limits, upper	0.13		
lower	0.09		

* Mean of 10 tests

Table 4

COMPARISON OF PROPERTIES FOR ORIGINAL AND SEWN 3-PLY POLYESTER THREAD

Property	Thread	Calculated 't'
Tex	Original Sewn needle	-16.93**
	Original Sewn bobbin	-11.71**
	Sewn needle Sewn bobbin	+2.14*
Breaking strength	Original Sewn needle	+6.63**
	Original Sewn bobbin	+5.26**
	Sewn needle Sewn bobbin	-2.38*
Tenacity	Original Sewn needle	+11.71**
	Original Sewn bobbin	+10.52**
	Sewn needle Sewn bobbin	-2.73*
Extension	Original Sewn needle	0
	Original Sewn bobbin	-2.06
	Sewn needle Sewn bobbin	-1.76
Loop strength	Original Sewn needle	+0.20
	Original Sewn bobbin	-2.14*
	Sewn needle Sewn bobbin	-2.19*
Knot strength	Original Sewn bobbin	+1.69
	Sewn needle Sewn bobbin	+0.41

* 't' is significant at the 95% level of probability
** 't' is significant at the 99% level of probability

Table 5

ANALYSIS OF BREAKING STRENGTH VARIANCE FOR SELECTED SECTION 3.2 JOINTS MADE FROM WEBBINGS G AND F

Effect or interaction	Number of levels	Number of degrees of freedom	Variance ratio
Joint (T)	2	1	0.91
Webbing (W)	2	1	5160 *
Length of overlap (L)	6	5	0.86
T × W	4	1	1.32
T × L	12	5	1.11
W × L	12	5	0.72
T × W × L + residual	24	5	variance 0.0159

*significant at 99.9% probability level

Table 6

MEAN BREAKING STRENGTHS FOR JOINTS ANALYSED IN TABLE 5

	G	F
Mean breaking strength, kN	2.57	6.28

Difference required between means to achieve significance at 99% probability level = 0.14

	Lap	Superimposed
Mean breaking strength, kN	4.40	4.45

Difference required between means to achieve significance at 99% probability level = 0.14

	Length of overlap, mm					
	80	120	160	240	320	400
Mean breaking strength, kN	4.42	4.47	4.51	4.38	4.42	4.35

Difference required between means to achieve significance at 99% probability level = 0.33

Table 7a

ANALYS[illegible] BREAKING STRENGTH VARIANCE FOR SECTION 3.2 LAP JOINTS W[illegible] STITCHING FAILURE USING WEBBINGS G, D, J AND F

Effect	Number of levels	Number of degrees of freedom	Variance estimate	Variance ratio
Webbing (W)	4	3	0.020	1.79
Length of overlap (L)	3	2	3.770	331 *
W × L + residual	12	6	0.011	-

Table 7b

MEAN BREAKING STRENGTHS FOR EFFECTS IN TABLE 7a

	G	D	J	F
Mean breaking strength, kN	1.04	1.10	0.90	0.98

	Length of overlap, mm		
	0	10	20
Mean breaking strength, kN	0	1.08	1.94

Table 7c

ANALYSIS OF BREAKING STRENGTH VARIANCE FOR SECTION 3.2 LAP JOINTS WITH STITCHING FAILURE USING WEBBINGS D, J AND F

Effect	Number of levels	Number of degrees of freedom	Variance estimate	Variance ratio
Webbing (W)	3	2	0.112	0.88
Length of overlap (L)	6	5	13.96	110 *
W × L + residual	18	10	0.127	-

Table 7d

MEAN BREAKING STRENGTHS FOR EFFECTS IN TABLE 7c

	D	J	F
Mean breaking strength, kN	2.75	2.65	2.92

	Length of overlap, mm					
	0	10	20	40	60	80
Mean breaking strength, kN	0	1.05	1.94	3.56	4.39	5.71

* Significant at the 99.9% probability level

Table 8

ANALYSIS OF BREAKING STRENGTH VARIANCE OF SECTION 3.2 JOINTS

Effect or interaction	Number of levels	Number of degrees of freedom	Variance ratio
Joint (T)	2	1	113*
Webbing (W)	4	3	107*
Length of overlap (L)	11	10	38.0*
T × W	8	3	13.4*
T × L	22	10	12.3*
W × L	44	30	1.7
TWL + residual	88	30	Variance 0.652

* Significant at 99.9% level of probability

Table 9

MEAN BREAKING STRENGTHS FOR SIGNIFICANT EFFECTS AND INTERACTIONS FOR JOINTS WITH 3-POINT DOUBLE W IN 3-PLY SEWING THREAD

	Lap	Superimposed
Mean breaking strength, kN	3.95	5.78

Difference required between means to achieve significance at 99% probability level = 0.46

	G	D	J	F
Mean breaking strength, kN	2.30	5.65	6.35	5.15

Difference required between means to achieve significance at 99% probability level = 0.66

Length of overlap, mm

	0	10	20	40	60	80	120	160	240	320	400
Mean breaking strength, kN	0	3.97	4.31	4.92	5.12	5.65	5.74	5.77	5.96	6.08	5.98

Difference required between means to achieve significance at 99% probability level = 1.20

	G	D	J	F
Lap	2.15	4.49	4.73	4.43
Superimposed	2.44	6.82	7.97	5.87

Difference required between means to achieve significance at 99% probability level = 0.98

Length of overlap, mm

	0	10	20	40	60	80	120	160	240	320	400
Lap	0	1.08	1.94	3.30	3.93	4.93	5.08	5.36	5.79	6.04	6.00
Superimposed	0	6.86	6.68	6.54	6.31	6.37	6.39	6.19	6.13	6.11	5.96

Difference required between means to achieve significance at 99% probability level = 2.12

Table 10

SE.M EFFICIENCIES FOR SECTION 3.2 JOINTS

Webbing	Lap joint strength at 400mm sewn overlap as % of unstitched webbing strength	Maximum lap joint strength as % of unstitched webbing strength	Length of sewn overlap, mm	Superimposed joint strength at 400mm sewn length as % of unstitched webbing strength
G	68	71	240	68
D	92	92	400	84
J	80	82	320	81
F	83	88	160	88

Table 11

SEAM STRENGTHS GIVEN BY VARIOUS STITCHING PATTERNS
EACH HAVING THE SAME NUMBER OF STITCHES

	Sewing pattern			
	Transverse*	Longitudinal**	Single W**	Zig-zag**
Length of webbing in seam, mm	60	64	15	34
3-ply seam strength, kN	1.76	1.23	1.21	1.61
Vâriance	0.023	0.001	0.007	0.004
99% confidence limits, upper	2.07	1.44	1.68	1.99
lower	1.44	1.01	0.74	1.24
2-ply seam strength, kN	1.07	1.08	0.87	1.04
Vâriance	0.011	0.005	0.017	0.002
99% confidence limits, upper	1.28	1.47	1.62	1.27
lower	0.85	0.69	0.13	0.81

* Mean of 5 results
** Mean of 3 results

Table 12

BREAKING STRENGTHS OF SEAMS MADE WITH A COMBINATION OF 2- AND 3-PLY SEWING THREADS

Seam construction*	Experimental seam strength,** kN	Predicted seam strength†, kN			
		P1	P2	P3	P4
2 3 2	0.704	0.750	0.766	0.741	0.693
3 2 3	0.838	0.900	0.870	0.894	0.849
2 3 3 2	1.082	1.100	1.106	1.090	1.016
3 2 2 3	0.922	1.100	1.106	1.090	1.016
3 2 3 2	0.972	1.100	1.106	1.090	1.016
3 3 2 3 3	1.546	1.600	1.530	1.592	1.535
2 2 3 2 2	1.076	1.150	1.148	1.133	1.130
3 2 3 2 3	1.266	1.450	1.488	1.439	1.355
2 3 2 3 2	1.218	1.300	1.248	1.286	1.200
2 3 3 3 2	1.440	1.450	1.488	1.439	1.355
3 2 2 2 3	1.438	1.300	1.248	1.286	1.200
3 3 3 2 2 2 3 3 3	2.250	2.700	2.718	2.683	2.547
2 2 2 3 3 3 2 2 2	1.722	2.250	2.256	2.223	2.079

* 2 = 2-ply sewing thread, 3 = 3-ply sewing thread

** Each value mean of 5 tests

† P1 = (number of rows in 3-ply × average breaking strength found for one row 3-ply seam) + (number of rows in 2-ply × average breaking strength found for one row 2-ply seam)

P2 = (Actual breaking strength for given number of rows in 3-ply) + (actual breaking strength for given number of rows in 2-ply)

P3 = (loop strength of 3-ply thread × R_3 × number of stitches in 3-ply) + (loop strength of 2-ply thread × R_2 × number of stitches in 2-ply) + (2 knotted stitches/row × number of rows in 3-ply) + (2 knotted stitches/row × number of rows in 2-ply)

P4 = $z = \left[z_2 + (z_3 - z_2)x - ax(1 - x)\right] n$ (see section 6.2)

Table 13a

PREDICTED SEAM STRENGTHS BASED ON 3-PLY SEWING THREAD

1	2	3	4	5	6	7	8	9
		Predicted seam strength based on thread property						
Number of transverse rows	Actual breaking strength of seam, (kN)	Original tensile, (kN)	Original tensile + 2 knotted stitches/row, (kN)	Sewn needle tensile, (kN)	Sewn needle tensile + 2 sewn needle knotted stitches/row, (kN)	Original loop, sewn needle loop, (kN)	Original knot, sewn needle knot, (kN)	½ sewn needle loop + 2 sewn needle knotted stitches/row, (kN)
1	0.35	0.35	0.40	0.32	0.37	0.48	0.20	0.29
2	0.69	0.70	0.81	0.64	0.75	0.95	0.39	0.58
3	1.07	1.05	1.21	0.96	1.12	1.43	0.58	0.88
4	1.35	1.39	1.62	1.28	1.50	1.90	0.77	1.17
5	1.76	1.74	2.02	1.60	1.87	2.38	0.96	1.46
6	2.16	2.09	2.43	1.92	2.24	2.85	1.16	1.75

Table 13b

PREDICTED SEAM STRENGTHS BASED ON 2-PLY SEWING THREAD

Number of transverse rows	Actual breaking strength of seam, (kN)	Predicted seam strength based on thread property					
		Original tensile, (kN)	Original loop, (kN)	Original knot, (kN)	Original knot + 2 knots/row, (kN)	Loop/2, (kN)	Loop/2 + 2 knotted stitches/row, (kN)
1	0.18	0.23	0.34	0.13	0.17	0.17	0.21
2	0.42	0.45	0.67	0.27	0.34	0.34	0.41
3	0.56	0.68	1.01	0.40	0.52	0.50	0.62
5	1.07	1.13	1.68	0.67	0.86	0.84	1.03
6	1.19	1.36	2.02	0.81	1.04	1.01	1.24
8	1.54	1.82	2.68	1.07	1.38	1.34	1.65

Table 14

ANALYSIS OF VARIANCE OF 3-PLY THREAD PROPERTIES FOR SEAM STRENGTH PREDICTION

Effect	Number of levels	Number of degrees of freedom	Variance ratio
Thread property (Q)	6	5	20*
Rows of stitching (S)	6	5	450**
Q × S + residual	36	25	Variance 0.006

* Significant at 99% level of probability
** Significant at 99.9% level of probability

Table 15

MEAN BREAKING STRENGTHS FOR PREDICTED SEAM STRENGTHS

	Transverse rows of stitching					
	1	2	3	4	5	6
Mean breaking strength, kN	0.35	0.69	1.05	1.38	1.74	2.10

Difference required between means to achieve significance at 99% probability level = 0.14

Thread property	Mean breaking strength, kN
Actual	1.23
Original tensile	1.22
Original tensile + knots	1.42
Sewn needle tensile	1.12
Sewn needle tensile + knots	1.31
Sewn needle loop/2 + knots	1.02

Difference required between means to achieve significance at 99% probability level = 0.14

Table 16a

PREDICTED STRENGTH FOR LAP JOINT SEWN WITH 3-POINT DOUBLE W IN 3-PLY THREAD

Length of overlap mm	Theoretical number of stitches	Predicted lap joint strength, kN	
		Without knotted stitches	With knotted stitches
10	22.2	0.94	0.99
20	44.4	1.87	1.93
40	88.8	3.74	3.80
60	133.2	5.62	5.67
80	177.6	7.49	7.54
120	266.4	11.23	11.28
160	355.2	14.98	15.03

Table 16b

PREDICTED STRENGTH FOR LAP JOINT SEWN WITH 3-POINT DOUBLE W IN 2-PLY THREAD

Length of overlap mm	Theoretical number of stitches	Predicted lap joint strength, kN	
		Without knotted stitches	With knotted stitches
20	44.4	1.00	1.04
30	66.6	1.50	1.54
40	88.8	2.00	2.04
60	133.2	3.01	3.04

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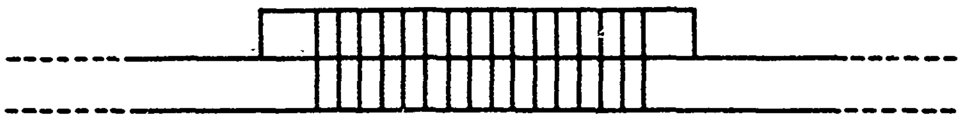
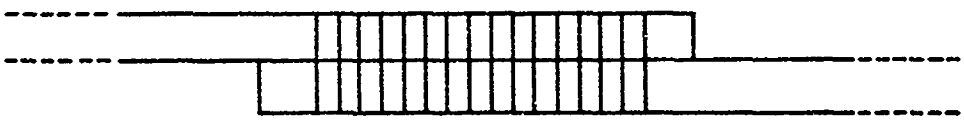
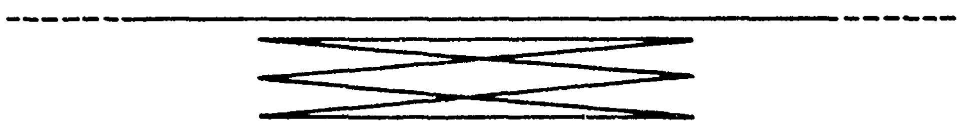


a Superimposed joint,
side elevation



b Lap joint, side elevation



c 3-point double W
stitching pattern, plan

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Fig. 1a–c Types of joint construction

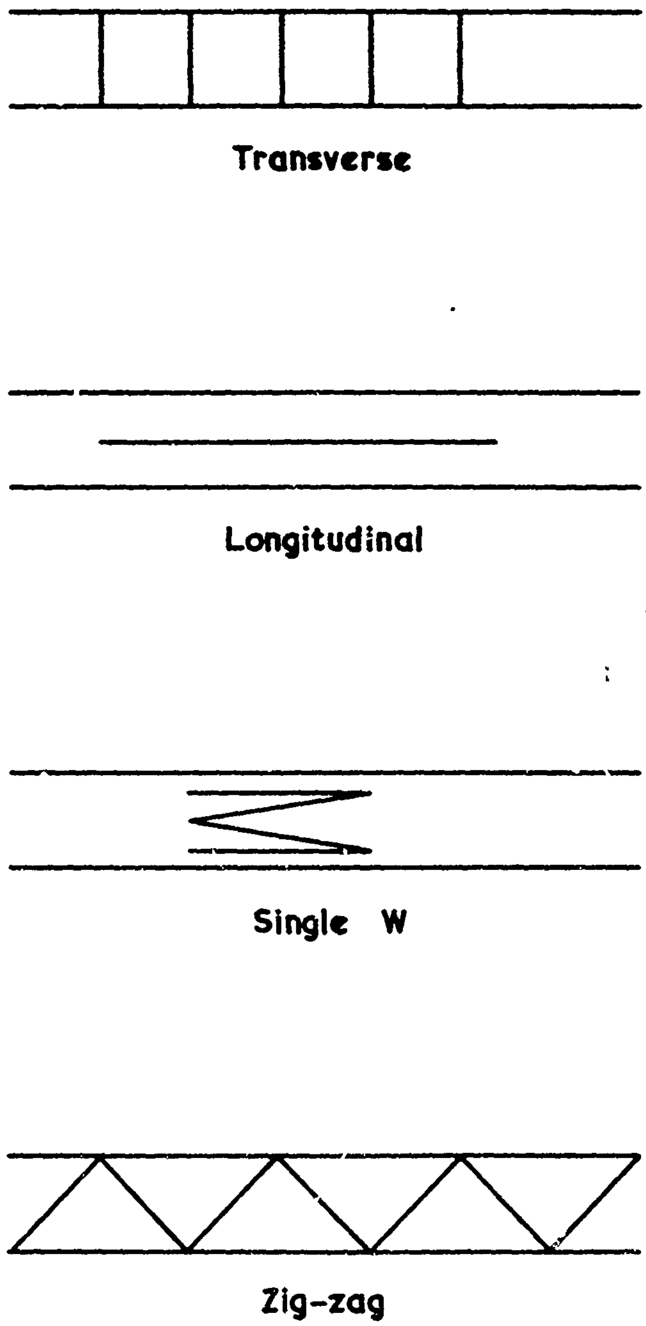

Fig. 2 Stitching patterns

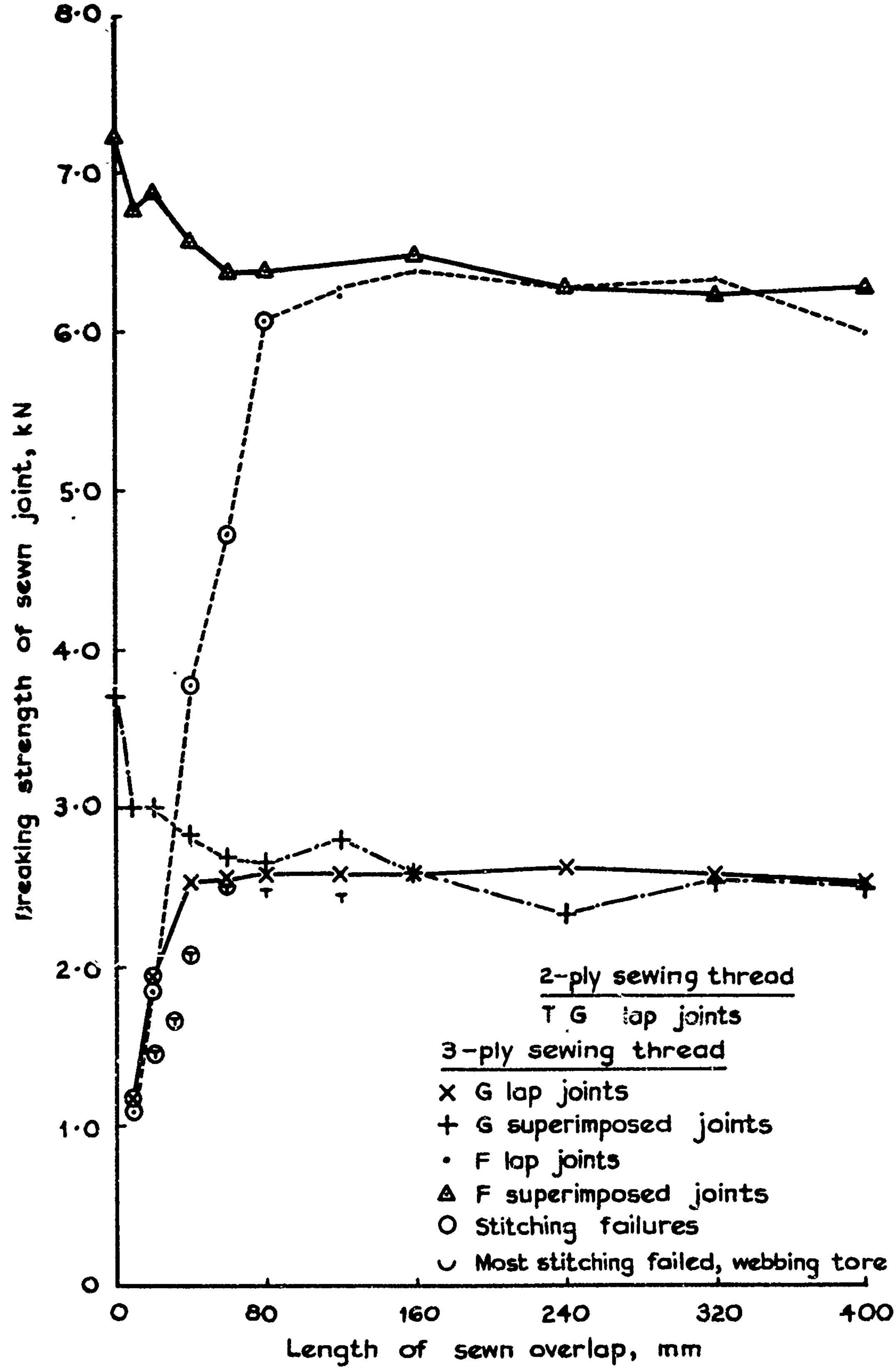

Fig. 3 Lap and superimposed joints in webbings F and G

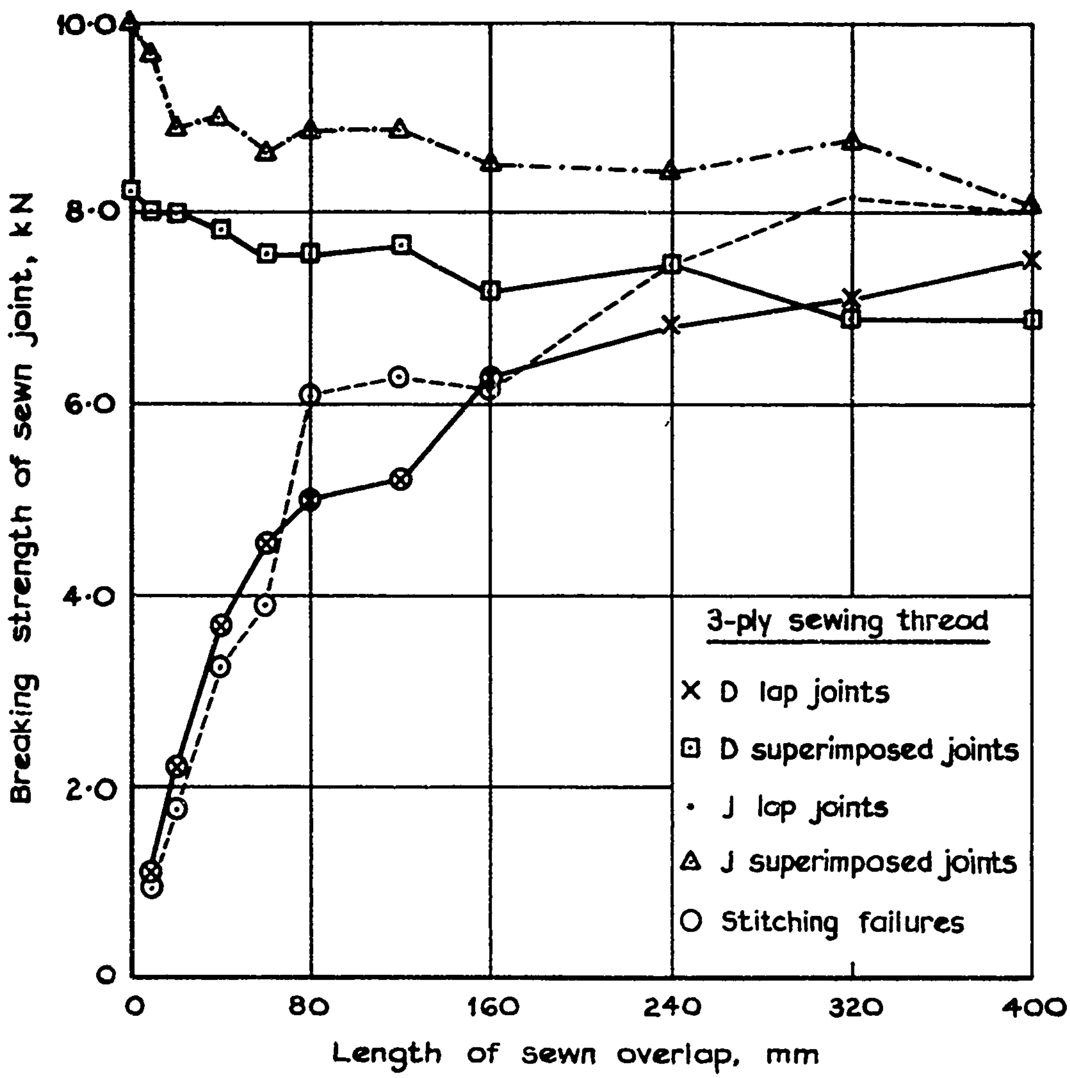

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Fig. 4 Lap and superimposed joints in webbings D and J

Fig. 5

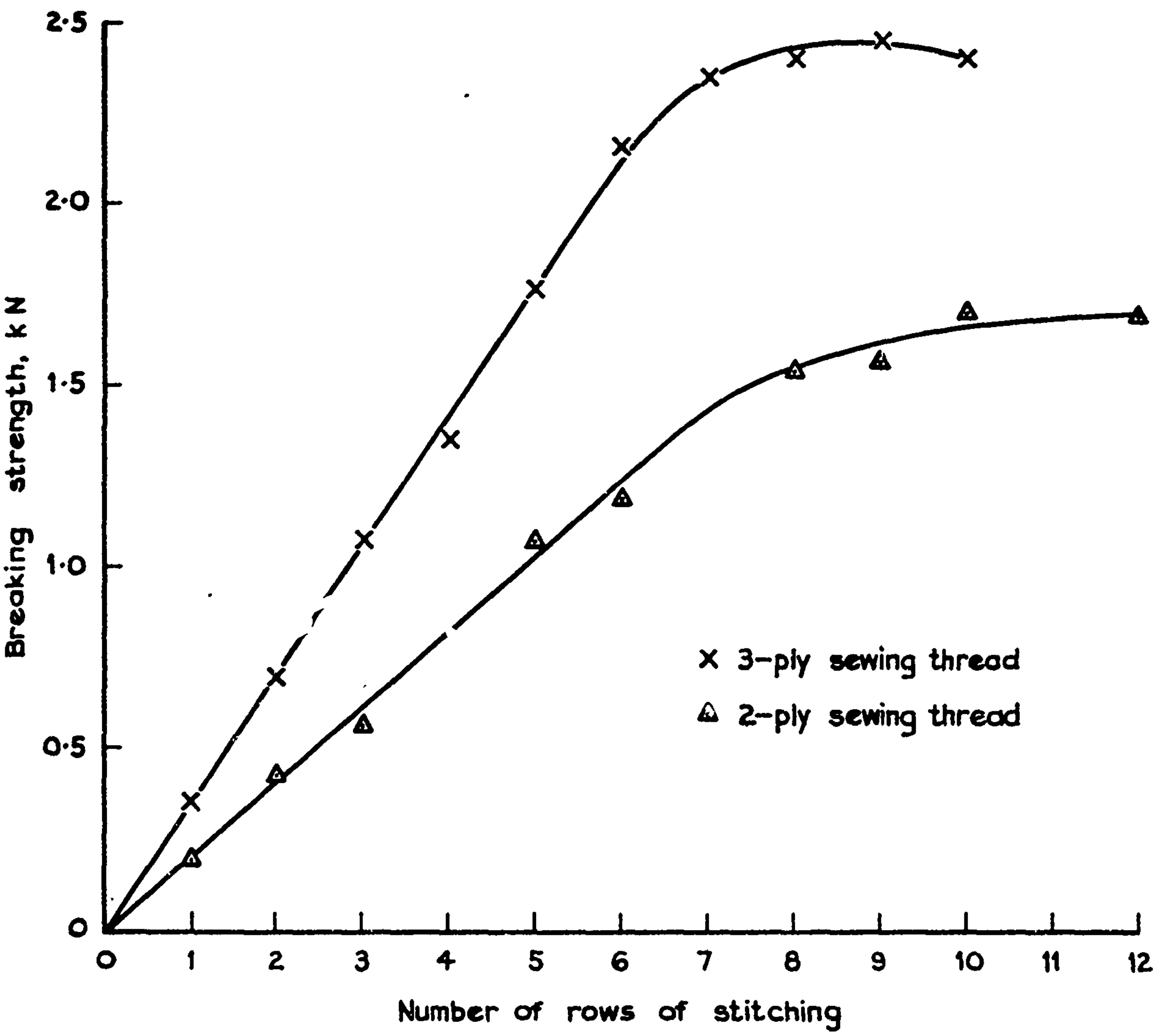

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Fig. 5 Seam strength as a function of increasing number of rows of transverse stitching.

Fig. 6

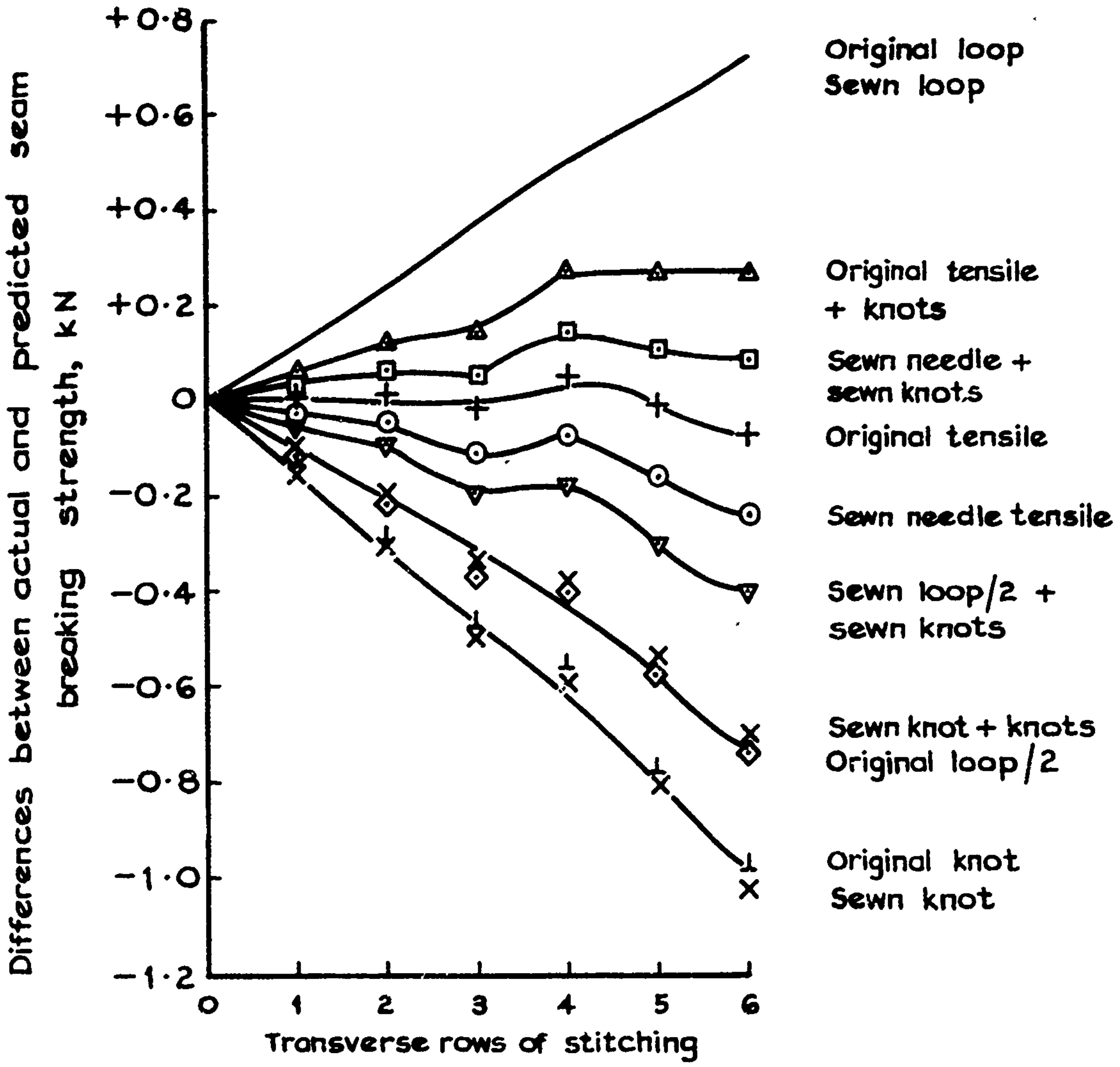

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Fig. 6 Differences between actual and predicted seam strength for 3- ply sewing thread

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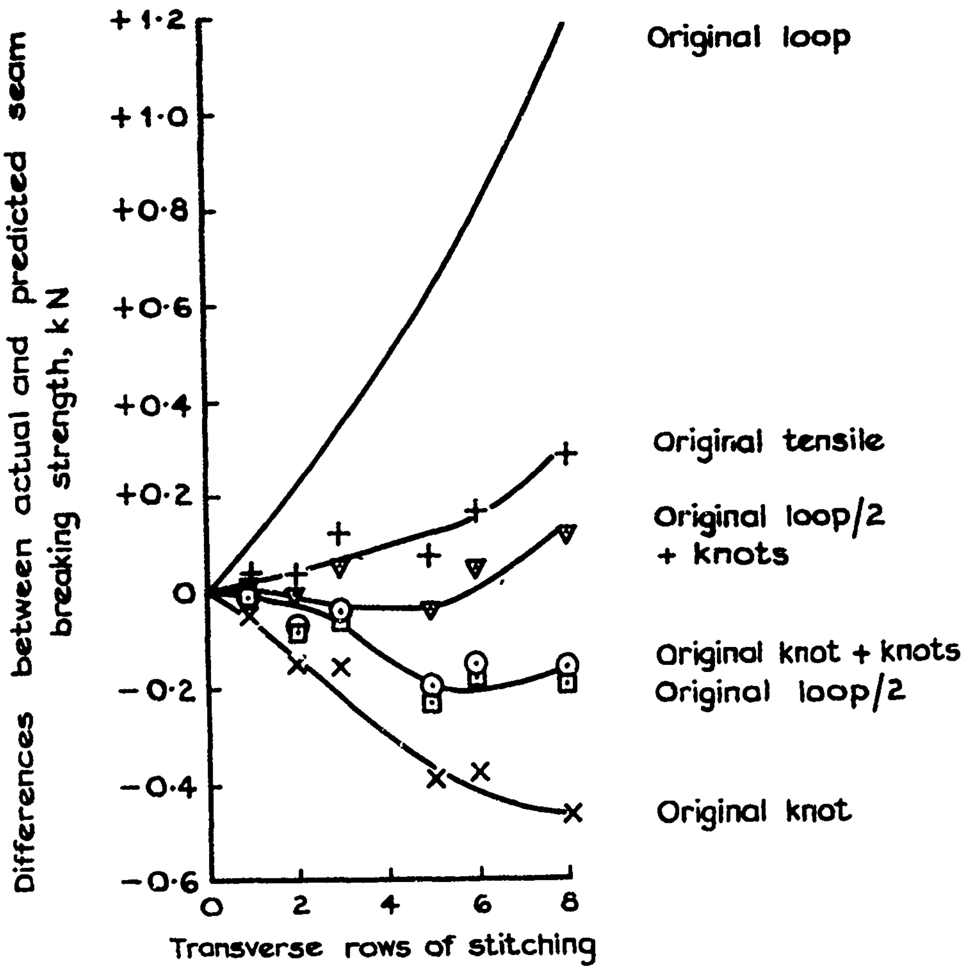

Fig. 7 Differences between actual and predicted seam strength for 2-ply sewing thread

Fig. 8

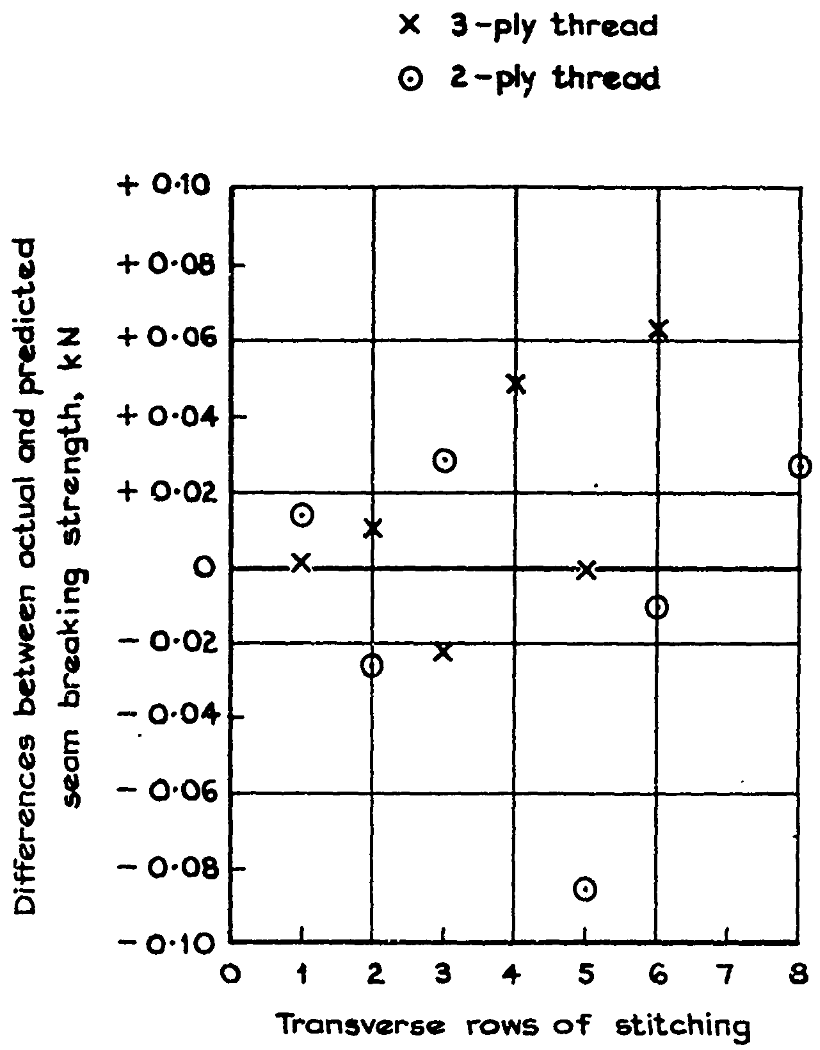

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Fig. 8 Differences between actual seam strength and prediction using loop strength x R for 3- and 2- ply sewing threads

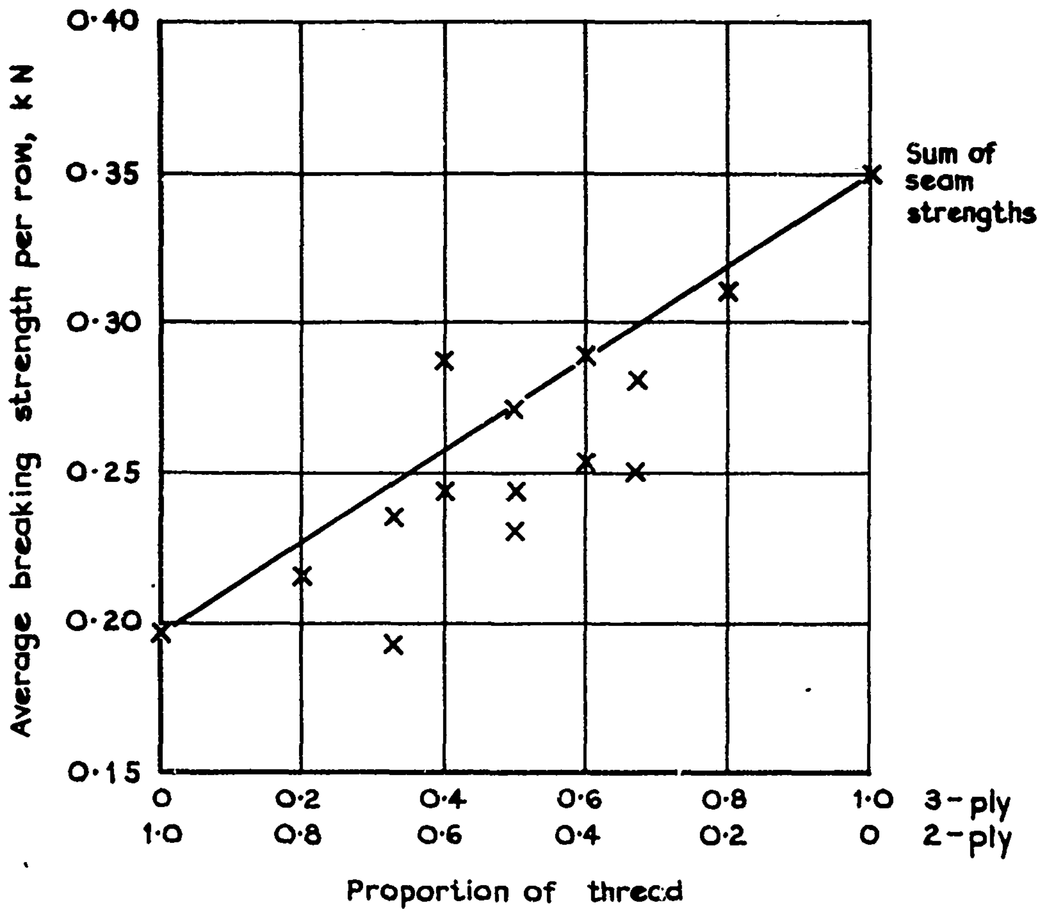

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Fig. 9 Average breaking strength per row for seams made with a combination of 2- and 3-ply sewing threads