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Analysis of Stresses and Elongations in Geomembranes

Two unexpected effects of stresses upon geomembranes are analyzed by the author. The extent to which the tensile behavior of an unreinforced geomembrane is affected by a non-uniform thickness is discussed in the first portion of the paper. Behavior of both geomembranes with yield and without yield is examined for several cases of non-uniform thickness, with portions of the analyzed geomembrane having lack of thickness and/or extra thickness. The author then explores transfer of stress through seams for both reinforced and unreinforced geomembranes. The importance of peel tests in evaluation of the stress capability of seams is emphasized. Conclusions drawn from these analyses and recommendations for designers of liners are then presented.

INTRODUCTION

Stresses in geomembranes result from a number of phenomena at different scales: stresses affecting large areas of the geomembrane may result from gravity, thermal expansion-contraction, and shrinkage; stresses affecting localized areas of the geomembrane usually result from differential behavior between two areas of the soil or structure supporting the geomembrane, such as differential settlement between earth dike and concrete structure, cracks in the supporting concrete or soil, and subsidence of a small area of the supporting soil.

Experienced designers are aware of the above mentioned stresses, but there is much less awareness, even among specialists, of concentrated stresses likely to occur at a much smaller scale due to discontinuities in geomembrane thickness. Such stresses might be the cause of unexplained failures. These stresses and the resulting elongations are discussed in the first part of this paper.

Also, stress transfer through a seam between two adjacent geomembrane sheets may not be as simple as usually assumed, and seam failure may be caused by forces smaller than expected. The influence of seam width on stress transfer through seams is discussed in the second part of this paper.

The two parts of this paper have in common the influence that geometrical characteristics such as geomembrane thickness and seam width have on stresses.

1 INFLUENCE OF A NON-UNIFORM THICKNESS ON GEOMEMBRANE TENSILE BEHAVIOR

1.1 Presentation of the Problem

It is usually implicitly assumed that geomembrane thickness is uniform. In fact, the thickness of a geomembrane may not be uniform for a variety of reasons such as: (i) manufacturing process (e.g., spread coating overlaps); (ii) insufficient control of manufacturing process; (iii) scratches on, or abrasion of the geomembrane, done during transportation or installation; (iv) grinding of the geomembrane for seaming preparation; (v) seaming; (vi) cap strips and patches; and (vii) abrasion of the geomembrane by materials in contact. A geomembrane can exhibit localized extra thickness as a result of (i), (v), and (vi), localized lack of thickness as a result of (iii), (iv), and (vii), and either one from (ii).

The purpose of the study presented hereafter is to evaluate the extent to which the tensile behavior of a geomembrane can be affected by a non-uniform thickness. The analyses are related exclusively to unreinforced geomembranes. The tensile behavior of most reinforced geomembranes is essentially governed by the reinforcing fabric and, for practical purposes, is not affected by a non-uniform thickness of the polymeric coating.

1.2 Tensile Behavior of a Uniformly Thick Unreinforced Geomembrane

A tensile test consists of recording the tensile force F necessary to progressively increase the length L of a geomembrane sample. Normalized results are obtained by dividing the force F by the sample width B to obtain the force per unit width α, and dividing the sample length increase ΔL by the initial length L to obtain the strain ε (also called elongation). As shown in Fig. 1, the force per unit width/elongation curves can be of two types for unreinforced geomembranes: (i) curves without yield are typical of PVC or butyl rubber geomembranes; and (ii) curves with a yield peak are typical of HDPE geomembranes.

For unreinforced geomembrane samples of uniform thickness T, it is possible to further normalize test results by dividing the force per unit width by the initial thickness to obtain the stress σ ($\sigma = \alpha / T$). A stress/elongation curve related to a given polymeric compound is valid for any geomembrane made of this polymeric compound, regardless of its thickness, while a force per unit width/elongation curve is valid only for one type of geomembrane (which includes thickness and polymeric compound). Using the stress/elongation curve, the secant modulus E at elongation ε of a polymeric compound can be defined as the ratio between the stress and the corresponding elongation [$E = \sigma/\varepsilon = \alpha/(\varepsilon T)$].

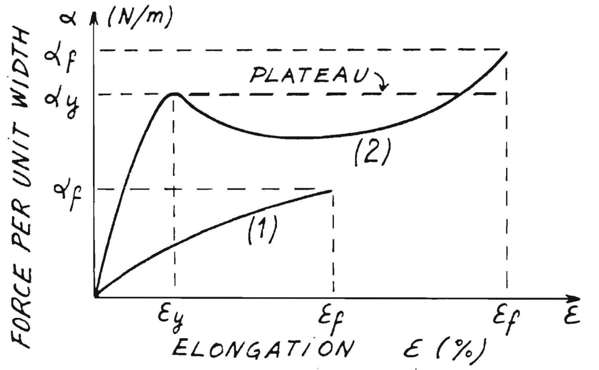

Fig. 1 Force per unit width/elongation curve without yield (1) or with yield (2). Notation: α_y = force per unit width at yield; α_f = force per unit width at failure; ε_y = elongation at yield; ε_f = elongation at failure. Note: depending on the polymeric compound and the thickness of the geomembrane, curve (1) can be above or below curve (2).

1.3 Elongation of a Non-uniformly Thick Geomembrane

The geomembrane samples considered in the theoretical study are defined in Fig. 2. When any of these samples is subjected to a tensile force, the force per unit width α is the same in any cross section parallel to the width B, but the stress σ in the portion of thickness T and the stress σ' in the portion of thickness T' are different as shown by the following equation which results from the definition of σ given above:

$$\alpha = \sigma T = \sigma' T' \qquad (1)$$

The stress/elongation curve is unique for a given polymeric compound. Therefore, as a result of the difference between σ and σ', the elongation ε in the portion of thickness T and the elongation ε' in the portion of thickness T' are different. However, an average elongation ε_a can be defined as the ratio between the sample length increase Δ L and the original length L. This results in:

$$L(1+\varepsilon_a) = (L-L')(1+\varepsilon) = L'(1+\varepsilon') \qquad (2)$$

Hence:

$$\varepsilon_a = \varepsilon(1 - L'/L) + \varepsilon' L'/L \qquad (3)$$

Combining Eq. 1 with the definition of the modulus given in Section 1.2 gives:

$$\alpha = E \varepsilon T = E' \varepsilon' T' \qquad (4)$$

Eliminating ε or ε' between Eqs. 3 and 4 gives the following two equations:

$$\varepsilon_a / \varepsilon' = L'/L + (1 - L'/L)(T'/T)(E'/E) \qquad (5)$$

$$\varepsilon_a / \varepsilon = (1-L'/L) + (L'/L)(T/T')(E/E') \qquad (6)$$

The elongation of the thin portion of the geomembrane sample is larger than the elongation of the thick portion. Therefore, the thin portion will reach the yield elongation ε_y (if any) and the elongation at failure ε_f before the thick portion. Therefore, the behavior of the sample is governed by the thin portion. Consequently, Eq. 5 will be used when T' is less than T, and Eq. 6 when T is less than T'.

The principle of the discussions presented in the next two sections is to compare the actual behavior of the geomembrane sample, i.e., the measured force per unit width and the measured elongation in a tensile test, with the nominal behavior of the geomembrane, i.e., the behavior of a sample of uniform thickness T (characterized by its force per unit width/elongation curve, (1) or (2) in Fig. 1).

1.4 Behavior of a Geomembrane Without Yield

Lack of Thickness In this case, ε' is larger than ε and failure occurs when $\varepsilon' = \varepsilon_f$. According to Eq. 5, the average elongation at failure is:

$$\varepsilon_{af} = \varepsilon_f \, [L'/L + (1 - L'/L)(T'/T)(E'/E)] \qquad (7)$$

The actual force per unit width at failure α_{af} is the force per unit width causing failure of (i.e., generating stress σ_f in) the portion of thickness T'. It is related to the nominal force per unit width at failure α_f by:

$$\alpha_{af} = \sigma_f \, T' = \alpha_f \, T'/T \qquad (8)$$

Extra Thickness In this case, ε is larger than ε' and failure occurs when $\varepsilon = \varepsilon_f$. According to Eq. 6, the average elongation at failure is:

$$\varepsilon_{af} = \varepsilon_f \, [(1-L'/L) + (L'/L)(T/T')(E/E')] \qquad (9)$$

The actual force per unit width at failure α_{af} is the force per unit width causing failure of the portion of thickness T. It is therefore equal to the nominal force per unit width at failure:

$$\alpha_{af} = \alpha_f \qquad (10)$$

1.5 Behavior of a Geomembrane With Yield

In the analysis presented in this section, the nominal force per unit width/elongation curve of the geomembrane (curve (2) in Fig.1) is approximated by a curve with a plateau after the peak. This simplifies the analysis without practically affecting the results.

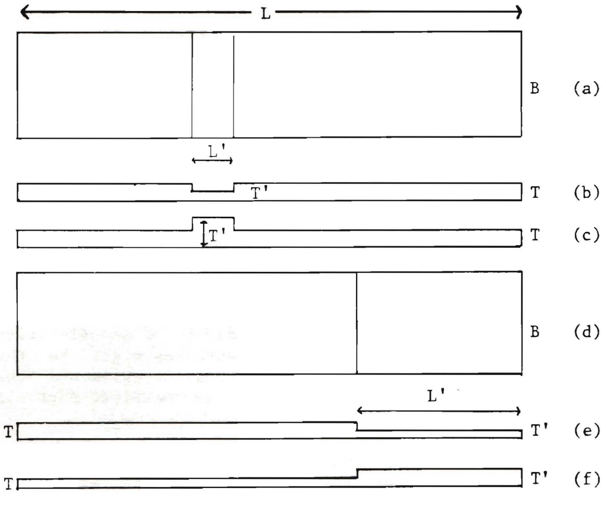

Fig. 2 Geomembrane samples considered in study: (a) Plan view for samples (b) and (c); (b) Sample with an indentation over length L'; (c) Sample with extra thickness over length L'; (d) Plan view for samples (e) and (f); (e) Sample with lack of thickness over length L'; and (f) Sample with extra thickness over length L'.

Lack of Thickness In this case, ε' is larger than and yield occurs when $\varepsilon' = \varepsilon_y$. According to Eq. 5, the average elongation at yield is:

$$\varepsilon_{ay} = \varepsilon_y \, [L'/L + (1-L'/L)(T'/T)(E'/E)] \qquad (11)$$

The actual force per unit width at yield α_{ay} is the force per unit width causing yield of (i.e., generating stress σ_y in) the portion of thickness T'. It is related to the nominal force per unit width at yield α_y, by:

$$\alpha_{ay} = \sigma_y \, T' = \alpha_y \, T'/T \qquad (12)$$

This force per unit width remains constant beyond the yield point. Therefore, the elongation ε in the portion of thickness T remains constant, while the elongation ε' keeps increasing until it reaches the elongation at failure ε_f. The constant value of ε corresponds to the force per unit width α_{ay} exerted on the portion of thickness T:

$$\varepsilon = (\alpha_{ay}/T)/E = \varepsilon_y \, (T'/T)(E'/E) \qquad (13)$$

The average elongation beyond the yield point can be determined by combining Eqs. 3 and 13:

$$\varepsilon_a = \varepsilon_y \, (1-L'/L)(T'/T)(E'/E) + \varepsilon' L'/L \qquad (14)$$

Hence, at failure:

$$\varepsilon_{af} = \varepsilon_y \, (1-L'/L)(T'/T)(E'/E) = \varepsilon_f \, L'/L \qquad (15)$$

Extra Thickness In this case, ε is larger than ε' and yield occurs when $\varepsilon = \varepsilon_y$. According to Eq. 6, the average elongation at yield is:

$$\varepsilon_{ay} = \varepsilon_y \, [(1-L'/L) + (L'/L)(T/T')(E/E')] \qquad (16)$$

The actual force per unit width at yield α_{ay} is the force per unit width causing yield of the portion of thickness T. It is therefore equal to the nominal force per unit width at yield:

$$\alpha_{ay} = \alpha_y \qquad (17)$$

This force per unit width remains constant beyond the yield point. Therefore, the elongation ε' in the portion of thickness T' remains constant, while the elongation ε keeps increasing until it reaches the elongation at failure ε_f. The constant value of ε' corresponds to the force per unit width α_y exerted on the portion of thickness T':

$$\varepsilon' = (\alpha_y/T')/E' = \varepsilon_y \, (T/T')(E/E') \qquad (18)$$

The average elongation beyond the yield point can then be determined by combining Eqs. 3 and 18:

$$\varepsilon_a = \varepsilon_y \, (L'/L)(T/T')(E/E') + \varepsilon \, (1-L'/L) \qquad (19)$$

Hence, at failure:

$$\varepsilon_{af} = \varepsilon_y \, (L'/L)(T/T')(E/E') + \varepsilon_f \, (1-L'/L) \qquad (20)$$

1.6 Numerical Examples

To illustrate the use of Eqs. 7 through 20, typical cases of lack of thickness or extra thickness have been considered. Values of the actual force per unit width at failure α_{af} and of the average elongation at failure ε_{af} have been calculated for two types of geomembranes: (i) a typical PVC geomembrane (without yield) with characteristics at failure $\alpha_f = 20$ kN/m and $\varepsilon_f = 400\%$; and (ii) a typical HDPE geomembrane, exhibiting yield, whose characteristics are $\alpha_y = 30$kN/m and $\varepsilon_y = 10\%$ at yield and $\alpha_f = 30$ kN/m and $\varepsilon_f = 700\%$ at failure. In this latter case, the actual force per unit width and the average elongation at yield were also calculated. Results are presented in Table 1.

The behavior of a geomembrane without yield is not significantly affected by typical thickness variations. At working elongations (typically 0 to 50%), the change in behavior is negligible.

The behavior of a geomembrane exhibiting yield is significantly affected, especially in two cases, one of lack of thickness, one of extra thickness:

- . A narrow scratch or crack reducing the thickness of the geomembrane by 25% does not affect the strength significantly, but does affect the elongation at yield which becomes 7.5% instead of 10%. Even more affected is the elongation at failure which becomes 14% instead of 700%. This result does not correspond

Table 1 Influence of lack of thickness [cases (a) and (b)] and extra thickness [cases (c), (d) and (e)] on the behavior of typical geomembranes without or with yield. Definitions of L, L', T and T' are given in Fig. 2. Calculated values are: actual force per unit width at failure α_{af} and average elongation at failure ε_{af}, for a geomembrane without yield (Section 1.4); and actual force per unit width at yield α_{ay} and at failure α_{af}, and average elongation at yield ε_{ay} and at failure ε_{af}, for a geomembrane with yield (Section 1.5).

		Given Geometry		WITHOUT YIELD Calculated with		WITH YIELD Calculated with $\alpha_y = \alpha_f = 30$ kN/m		
				$\alpha_f = 20$ kN/m	$\varepsilon_f = 400\%$		$\varepsilon_y = 10\%$	$\varepsilon_f = 700\%$
		L'/L (-)	T'/T (-)	α_{af} (kN/m)	ε_{af} (%)	$\alpha_{ay} = \alpha_{af}$ (kN/m)	ε_{ay} (%)	ε_{af} (%)
(a)	Scratch, Crack	0.01	0.75	15	301	22.5	7.5	14
(b)	Lack of thickness over a large area	0.5	0.9	18	380	27	9.5	354
(c)	Seam	0.2	2	20	360	30	9	561
(d)	Patch, Cap strip	0.5	2	20	300	30	7.5	352
(e)	Extra thickness over a large area	0.5	1.1	20	382	30	9.5	354

to an extreme academic case but to a likely situation. In fact, failures of this type have been observed (1). Consequently, the following important recommendation can be made: the elongation to be considered when designing a liner using a geomembrane exhibiting yield should be smaller than an allowable elongation obtained by dividing the elongation at yield by a certain factor. Further studies should be undertaken to determine this factor. Tentatively, using a value of 2 for this factor can be considered to include: (i) the above mentioned reduction of elongation at yield; (ii) the effect of creep which usually affects the behavior of geomembranes exhibiting yield; (iii) the possible smaller elongation in the field biaxial situation as compared to a laboratory uniaxial test; and (iv) a factor of safety.

- An extra thickness over a large area (e.g., a patch or a cap strip) also tends to concentrate stresses in the portion of the geomembrane having the nominal thickness. As a result the average elongation at yield is significantly affected. This is important because this elongation governs the ability of the geomembrane to withstand field situations where a given elongation is imposed to the geomembrane.

Finally, although the study presented above has been restricted to unreinforced geomembranes, a similar approach can be used to analyze the behavior of a reinforced geomembrane after failure of the reinforcing fabric. A large elongation occurs in the then unreinforced small portion, while the elongation remains small in the portion where the reinforcing fabric is still intact.

2 STRESS TRANSFER THROUGH A SEAM

2.1 Seam Tests

Two types of tests are used to evaluate geomembrane seam strength: the peel test and the shear test (Fig. 3).

Peel Test The force per unit width causing a seam to fail in a peel test does not depend on the geomembrane thickness: its value is typically between 1 and 3 kN/m (5 and 20 lb./in.). Such values are small, compared with the force per unit width at failure in a tensile test on a geomembrane sample without seam for which typical values are between 4 and 70 kN/m (25 and 400 lb./in.), depending on the thickness of the geomembrane. However, there is an exception: seams in HDPE geomembranes do not normally fail in peel. In other words, the peel adhesion of a HDPE geomembrane is at least equal to its tensile strength, regardless of the thickness.

In addition, reinforced geomembrane may have a small ply adhesion, i.e., a small adhesion between the reinforcing fabric and the polymeric compound. Many reinforced geomembranes have a ply adhesion smaller than peel adhesion. Such geomembranes may fail by delamination next to a seam when the seam is subjected to a peel test.

Shear Test The force per unit width causing a seam to fail in a shear test is usually 80 to 90% of the force per unit width at failure in a tensile test on a geomembrane sample without seam. However there is an exception: for HDPE geomembranes, the above ratio is usually 100%.

The special behavior of HDPE geomembranes in peel and shear tests suggests that the two tests may not be independent. In other words, the performance of seams of

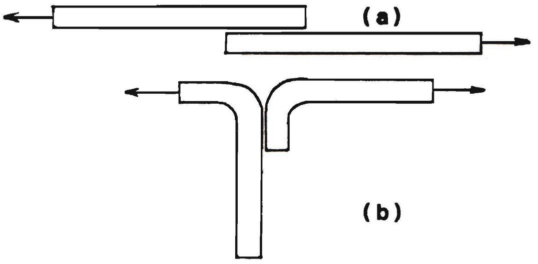

Fig. 3 Seam tests: (a) shear test; (b) peel test.

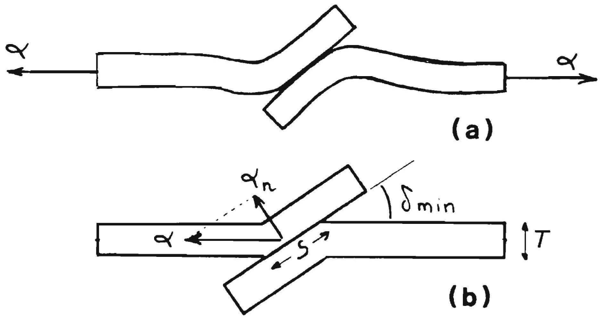

Fig. 4 Sample with a seam subjected to a shear test: (a) likely shape of the seam; (b) approximate shape used in calculations.

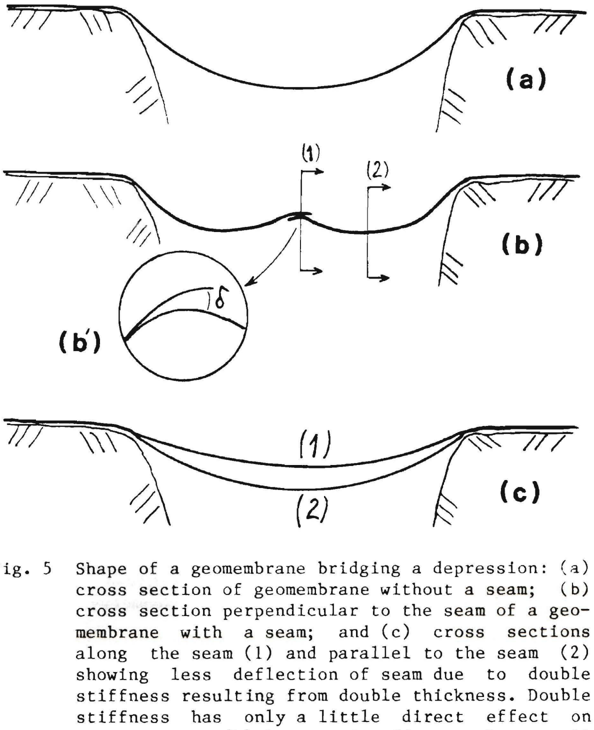

Fig. 5 Shape of a geomembrane bridging a depression: (a) cross section of geomembrane without a seam; (b) cross section perpendicular to the seam of a geomembrane with a seam; and (c) cross sections along the seam (1) and parallel to the seam (2) showing less deflection of seam due to double stiffness resulting from double thickness. Double stiffness has only a little direct effect on cross section (b) because it affects only a small portion of this cross section, but the geomembrane shape in cross section (b) is significantly affected by continuous stiffness of the seam in cross section (c1). Such tridimensional effect would not exist if the depression was an infinitely long trough perpendicular to cross section (b).

geomembranes other than HDPE when subjected to a shear test may be affected by their small peel adhesion. This is discussed in the following sections.

2.2 Peel Component in a Seam Shear Test

When a geomembrane sample with a seam is subjected to a shear test, the center of the seam tends to align itself with the direction of the applied force (Fig. 4a). As a result, the seam rotates and probably does not remain plane. Therefore, it is difficult to define an angle of rotation of the seam. However, as shown in Fig. 4b, a minimum value δ_{min} of the angle of rotation can be defined as follows:

$$\delta_{min} = \sin^{-1}(T/S) \qquad (21)$$

where: T = geomembrane thickness; and S = seam width.

As shown in Fig. 4b, the force per unit width α applied to the sample has a component α_n normal to the plane of the seam:

$$\alpha_n = \alpha \sin \delta_{min} \qquad (22)$$

The seam may fail by peeling or by delamination if the normal component α_n is larger than peel adhesion. To minimize the risk, the angle δ_{min} should be as small as possible. Combining Eqs. 21 and 22, it appears that at least the following condition should be satisfied to ensure that α_n is smaller than ply adhesion:

$$S/T > \alpha_f / \alpha_p \qquad (23)$$

where: S = seam width; T = geomembrane thickness; α_f = force per unit width at failure in a tensile test on a geomembrane sample without seam; and α_p = peel adhesion or ply adhesion, whichever is less.

Eq. 23 is necessary but not sufficient since δ_{min} defined by Eq. 21 is only a minimum value for the angle between the plane of the seam and the direction of the forces (as discussed in section 2.3). For a given geomembrane (characterized by T, α_f and α_p) a minimum seam width can be calculated using Eq. 23. Typical examples are presented in Table 2. The following comments can be made:

- The minimum seam width calculated according to Eq. 23 varies over a wide range, from 0.6 mm to 65 mm (0.02 in. to 2.58 in.).
- The required seam length increases when the thickness and the tensile strength of the geomembrane increase, the main factor being the tensile strength.
- Reinforced geomembranes require wider seams than unreinforced geomembranes due to their high tensile strength and low peel or ply adhesion. This is particularly true for heavily reinforced geomembranes because they have a low ply adhesion value as a result of small strike through (i.e., small openings of the reinforcing fabric, through which the polymeric compound on one side of the fabric can adhere to the polymeric compound on the other side of the fabric). In many instances seam width for reinforced geomembranes is 25 mm (1 in.) which is not sufficient for heavily reinforced geomembranes according to Eq. 23, as shown in Table 2.
- Seam width required for unreinforced geomembranes is smaller than 12 mm (1/2 in.). Typical 25 mm (1 in.) wide seams can therefore be considered as satisfactory for unreinforced geomembranes. From the point of view of Eq. 23, HDPE geomembranes constitute the ideal case where peel adhesion is at least equal to tensile strength which results in a very narrow required seam.

The above comments should not be isolated from their context. Stress transfer through a seam is a complex phenomenon and Eq. 23, based on simple assumptions, can be considered only as an approach leading to qualitative results. Values presented in Table 2 and discussed above should be used only to identify trends, such as the need for using wider seams for reinforced geomembranes than for unreinforced geomembranes.

While a thorough theoretical analysis of stress transfer through a seam would be complex, testing seams is relatively simple. Systematic testing of seams should be carried out to evaluate experimentally the influence of parameters identified in the above discussion.

2.3 Peel Components in Field Situations

The analysis presented in the previous section considered only forces in the cross section of a seam (Fig. 4). Such bidimensional analysis is not sufficient in some field situations where forces perpendicular to the considered cross section play an important role. A geomembrane bridging a depression is a typical example. The shape of the geomembrane with and without a seam is different, as explained in Fig. 5, due to seam stiffness in the direction perpendicular to the considered cross section.

As a result of the shape of the geomembrane shown in Fig. 5b, the two geomembrane sheets tend to exhibit an angle δ (Fig. 5b′) larger than the minimum value δ_{min} defined by Eq. 21 and Fig. 4. The observed value δ_{max} between the loose flap of the seam and the geomembrane can be considered as an upper boundary for δ . A value of the order of 30° has been observed by the author for δ_{max} on the seam of an unreinforced geomembrane bridging the corner of a reservoir after having undergone shrinkage. It may therefore be assumed that values of the order of 5 to 10° for δ are possible for unreinforced geomembranes. Values for δ are expected to be smaller for reinforced geomembranes than for unreinforced geomembranes since reinforced geomembranes are less deformable and consequently exhibit less deflection when bridging a cavity. Expected values for δ should be compared with the angle δ_ε to which a seam can resist when subjected to a force per unit width corresponding to a certain elongation of the geomembrane. According to Eq. 22, this angle does not depend on the seam length and its value is given by:

$$\delta_\varepsilon = \sin^{-1}(\alpha_p/\alpha_\varepsilon) \qquad (24)$$

where: α_p = peel adhesion or ply adhesion, whichever is less; and α_ε = force per unit width in the geomembrane at a given elongation ε .

Values of δ_{10} corresponding to a 10% elongation are given in Table 2. It appears that heavily reinforced geomembranes can withstand only small angles (2 to 4°) resulting from three dimensional phenomena such as the one depicted in Fig. 5. This results from the low adhesion compared with the high tensile forces existing in a reinforced geomembrane, even at small elongation. On the contrary, unreinforced geomembranes can withstand very large angles. Even at a 50% elongation, the accepted angle would still be larger than 30° for all unreinforced geomembranes considered in Table 2.

2.4 Conclusions Regarding Stress Transfer Through Seams

Due to small values of peel adhesion of all geomembranes except HDPE, seams are the weakest part of a geomembrane because in field situations, and even in a laboratory seam shear test, seams are subjected to peel

Table 2 Required seam width calculated using Eq. 23, and maximum seam angle at 10% elongation of the geomembrane calculated using Eq. 24. Tensile strength, and peel and ply adhesion values are from NSF standards (2).

REINFORCEMENT			UNREINFORCED				LIGHTLY REINFORCED		HEAVILY REINFORCED			
Polymeric Compound			PVC			HDPE	CSPE (Hypalon)					EIA
Thickness	T	mm mils	0.25 10	0.75 30	1.14 45	2.5 100	0.75 30	0.91 36	0.91 36	1.14 45	1.5 60	0.75 30
Tensile Strength	α_f	kN/m lb/in	4 23	12 69	18 104	26 150	17.5 100	21 120	35 200	35 200	52.5 300	70 400
Minimum (Peel, Ply) Adhesion	α_p	kN/m lb/in	1.75 10	1.75 10	1.75 10	26 150	1.75 10	1.75 10	1.2 7	1.2 7	1.2 7	1.4 8
Tensile Strength/Minimum Adhesion	α_f/α_p	-	2.3	6.9	10.4	1	10	12	29	29	43	50
Required Seam Width (Calculated with Eq. 23)	S	mm in	0.6 0.02	5.2 0.21	12 0.47	2.5 0.10	7.5 0.30	11 0.44	26 1.03	32 1.29	65 2.58	38 1.50
Force per unit width at 10% elongation	α_{10}	kN/m lb/in	0.2 1	0.5 3	0.9 5	26 150	9 50	10.5 60	17.5 100	17.5 100	26 150	35 200
Maximum Seam Angle at 10% elongation (Calculated with Eq. 24)	δ_{10}	°	90	90	90	90	12	10	4	4	3	2

stress components. The theoretical study presented above is based on simple assumptions and the obtained numerical values should only be considered as a means to express qualitative trends. It appears that the weakening of seams caused by insufficient peel adhesion is more marked for heavily reinforced geomembranes than for lightly reinforced or unreinforced geomembranes. Further studies including refined theoretical analyses and systematic laboratory testing should be undertaken to verify the findings of the preliminary approach presented herein. If these findings were confirmed, it could be concluded that seams for heavily reinforced geomembranes should be wider than for other geomembranes.

As for now, it is suggested that the peel test be considered not only as an index test for seam quality control but also as a means to evaluate the ability of a seam to withstand actual stress components in the field.

CONCLUSIONS

The study presented in the first part of this paper, although it could be further refined, leads to a clear conclusion: geomembranes exhibiting yield should always be used in situations where the elongation is smaller than an allowable elongation obtained by dividing the elongation at yield by a factor which may be of the order of 2. Ignoring this recommendation can lead to failures, just as lack of recognition of this phenomenon has led to failures in the past. With the increasing use of yield and creep-prone geomembranes, which is justified by some other desirable characteristics, a thorough knowledge of geomembrane mechanical behavior is required on the part of designers.

The study presented in the second part of this paper does not lead to clear-cut conclusions because the assumptions considered may be simplistic. Nonetheless, a trend has been identified: heavily reinforced geomembranes seem to require wider seams than lightly reinforced or unreinforced geomembranes. Due to the importance of the subject and the difficulty of theoretically analyzing stress transfer through a seam, a systematic testing program is recommended.

The two studies presented in this paper confirm that common sense in engineering is as reliable as tossing a coin, and more dangerous since it is more believable. Common sense dictates that a geomembrane exhibiting 700% elongation cannot fail in actual situations where imposed elongations rarely exceed 50% and only in limited areas. However, such a geomembrane can indeed fail under a 15% elongation as shown by analysis and experience. Again, common sense dictates that the stronger the reinforcement, the higher the factor of safety. However, in the cases discussed in this paper, a strong reinforcement may decrease the safety of seams. The same may occur in cases not discussed in this paper, such as differential settlements, where a stiff reinforcement is clearly detrimental.

It is hoped that the discussions presented in this paper will increase designers' awareness of the need for a thorough knowledge of geomembrane mechanical behavior to meet the challenges of liner design. It is also hoped that more extensive research work will be undertaken to better understand the mechanical behavior of geomembranes.

This paper results from personal and independent work done by the author, using published information and personal observations. The technical content of this paper has not been discussed prior to publication and is therefore the author's sole responsibility. Since some of the results and comments presented in this paper may have important practical consequences, the author requests that quotations from this paper not be isolated from relevant context.

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