BIAXIAL TESTING OF GEOGRIDS: RECENT DEVELOPMENTS

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Abstract: At different recent German and international conferences some publications discussed a so-called biaxial effect of geogrid reinforcement. Generally it is reported that synthetic materials (e.g. membranes used for roofing or in aeronautic applications) show somewhat different mechanical behaviour when loaded under biaxial stress conditions compared to uniaxial stress conditions. In the case of geogrid reinforcement it is the production technology, especially the formation of the crosspoints between the reinforcement elements of the longitudinal direction (MD) and the cross direction (CMD), which was declared to be the basic reason for this phenomenon. When loaded biaxially, geogrid reinforcement products made from punched and stretched polymer sheets and those made from welded or glued strips would perform significantly better (stiffer) than woven or knitted materials. The positive effect of biaxial loading would be apparent especially when analysing the creep-strain-behaviour of the materials.

The interpretations and conclusions basically with regard to the derivation of reduced reduction factors for creep-rupture are critically reviewed in this paper. Based on an extensive literature study, FEM-simulations as well as additional biaxial testing it is intended to further contribute to the ongoing discussion and research.

This paper will present that the effect of boundary conditions for biaxial testing especially the clamping and loading arrangement needs to be carefully considered to avoid misinterpretation of test results.

Keywords: geogrid reinforcement, biaxial stiffness, creep, stiffness, strain, testing

INTRODUCTION

Knowledge about the characteristic stress-strain behaviour of a construction material is fundamental for the design of any structure in civil engineering. In order to develop this knowledge on one hand, but also to improve the testing itself, research and development has always been very extensive in this field.

Biaxial and multiaxial material testing is a very specific and comparably young discipline within this complex. Nevertheless fundamental work has been reported already in 1985, Blum *et al*. (1985). This has been of special interest for the confection and the design of pretension-forces of membrane structures produced from different kinds of woven fabric, synthetic membranes or composite materials. These structures are very popular in modern architecture, e.g. Berthold *et al.* (2000), Koch (2004) or Seidel (2008). Latest papers dealing with the design of membrane structures, e.g. Bögner (2004), Wagner (2007) or Karwath *et al.* (2007), formulate material specific constitutive laws which allow to predict the deformation behaviour of those materials subjected to biaxial stress conditions. Other applications for biaxial testing can be found in the aeronautic industry, Krause, D. *et al.* (2001).

Nimmesgern, M. (1994) and Shinoda *et al*. (2004) but mainly Kupec (2004) and McGown *et al.* (2004) can be considered the first who have adopted biaxial material testing for geosynthetic products, in particular geogrids.

Although above mentioned application areas can be considered very specific and the materials used are quite different, there still is a significant similarity to be noted, especially when focusing on the testing itself. Regardless the application it is obvious that

- loading arrangement,
- clamping, and related matters,
- sample shape and size and
- strain measurement

are key points for successful biaxial testing.

Inappropriate testing can have a significant influence on the results and may cause misunderstanding of the real material behaviour. Hence it is important to perform testing and analysis with great care.

A careful review of the latest publications about biaxial testing of geogrids generated a lot of open questions and showed the need for additional testing, using an improved methodology to avoid such misinterpretation.

BIAXIAL TESTING OF GEOGRIDS

Loading arrangement

Figure 1 shows the schematic loading arrangement of two different biaxial test equipments. Both arrangements use cruciform shaped samples which have generally proven to be good for biaxial testing, e.g. Böhmert (1981), Blum *et al.* (1985), Bush *et al.* (1992).

The difference between both arrangements is obvious: the arrangement shown in Figure 1, left side, allows for a similar displacement of only two clamps whereas the second arrangement, Figure 1, right side, enables the displacement of all four clamps. The problem that is related to this difference is visible in Figures 2 and 3.

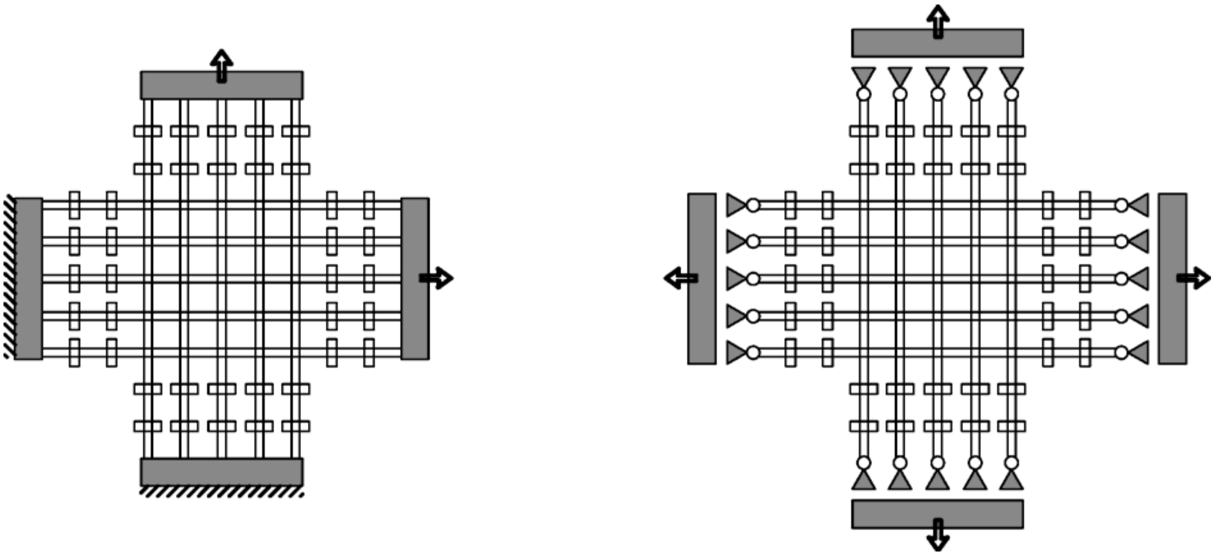

Figure 1. Left: inadequate loading arrangement (equipment at University of Strathclyde now RWTH-Aachen, McGown *et al.* (2004); Right: improved biaxial loading (equipment at University of Duisburg / Essen)

Figures 2 and 3 show photographs which are taken before and during a biaxial tensile test of a woven geotextile using the testing equipment of the University of Strathclyde, UK, which has recently been shifted to RWTH Aachen in Germany: The centre point of the specimen, marked in red colour, moves to the position which is marked green. Without even analysing measuring data in detail it seems to be logic that the distribution of stresses will not be homogeneous for the configuration adopted in the equipment at Strathclyde / Aachen. Improved biaxial loading arrangements have been developed e.g. by Blum *et al.* (1985) or Saxe *et al.* (1991). Figure 1, right side shows the schematic loading arrangement adopted in that case, Figure 5 shows corresponding equipment available at University of Essen, Saxe *et al.* (1991). Detailed information about the basic requirements for appropriate biaxial tensile testing is also given in a Japanese testing standard for membrane materials, Membrane Structures Association of Japan (1995).

Much better results can be expected when using a configuration as shown in Figure 1, right side: The centre point of the sample will not move during the entire test, regardless of the load ratio between both loading axes.

These pictures clearly demonstrate that homogeneous loading conditions can only be expected when appropriate equipment is used.

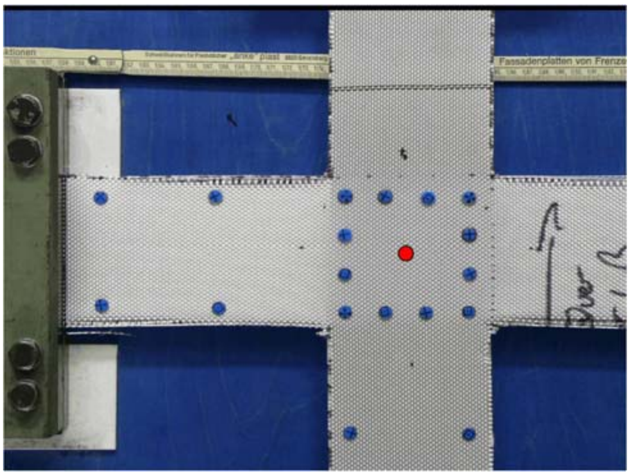

Figure 2. Biaxial testing of a woven geotextile at RWTH Aachen, begin of loading

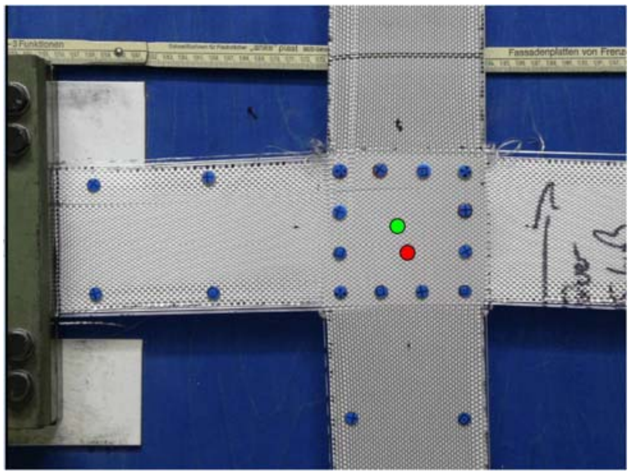

Figure 3. Biaxial testing of a woven geotextile at RWTH Aachen, situation just before break

Clamping, sample shape and size

Literature study has shown that most biaxial testing has been carried out with flexible materials like polymeric membranes, woven textiles or composite materials including woven textiles. This is important to note when analysing the clamping conditions and the stress distribution within the specimen. Clamping is primarily performed by means of screwed steel plates or capstan clamps, geogrid samples have been embedded in a special resin. At least for membrane type materials clamping conditions are therefore somewhat similar to those used for uniaxial testing. However regardless of the clamping detail used – any deformation perpendicular to the principle loading direction is always blocked in the clamp itself.

To eliminate this problem it is common practice to prepare the specimen in cruciform shape where the dimensions of the cross need to be sufficiently big. In addition to that it is essential to partly cut the cross-direction of the material in a specific zone between the clamp and the centre portion that is considered the representative specimen area.

Elaborate laboratory testing at the University of Essen has shown that the specimen preparation is very sensitive and may vary depending on the specific product, Neberg (1989).

Figure 4 shows a new approach to this problem. In case of geogrids it is possible to apply single strip clamping. Every single clamp has a spherical shape to enable full rotational flexibility of all strips.

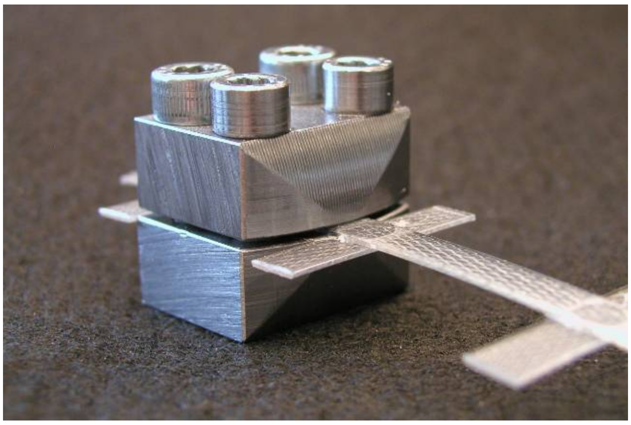

Figure 4. Single strip clamping of geogrid developed for biaxial testing at University of Essen

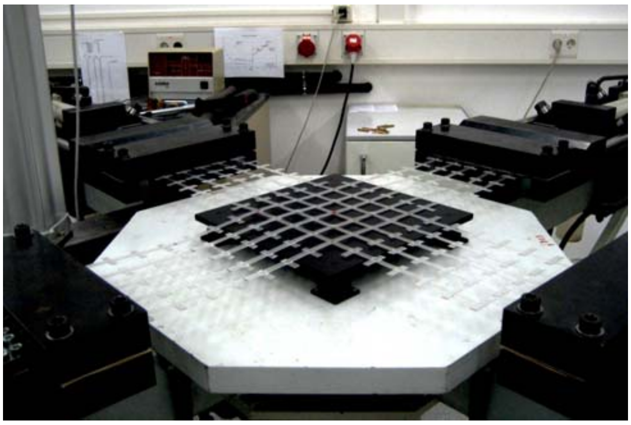

Figure 5. Biaxial testing equipment at University of Essen

Constant Rate of Strain Testing (CRS-testing)

Constant-Rate-of-Strain testing (CRS) was carried out in order to verify that the improvements in the loading arrangement for the biaxial testing especially the clamping arrangement work properly.

Table 1 provides a compilation of materials used for biaxial testing at the University of Strathclyde Kupec (2004). This shows that complete reference for CRS-testing (biaxial and uniaxial) is available only for Geogrid types A, B, and C, whereas the woven material, type D, was not tested. In regard of that as well as to the fact that most post analyses was published for a welded geogrid made of Polyester (PET), geogrid type B in Table 1, e.g. Heerten *et al.* (2005), McGown *et al.* (2004), it was decided to start new tests using this product. Further to that it was decided to use the same specimen sizes and comparable strain rates.

Table 1. Compilation of biaxial testing at University of Strathclyde

Geogrid				**Type of testing**			
Type		**Polymer**	**Nominal Strength MD / CMD †**	**Constant Rate of Strain (CRS) ‡**		**Sustained Loading (Creep) ‡**	
			[kN/m]	**Uniaxial**	**Biaxial §**	**Uniaxial**	**Biaxial §**
Welded	A	PP	60 / 60	Tested	Tested	Tested	Tested
Welded *	**B**	**PET**	**60 / 60**	**Tested**	**Tested**	**Tested**	**Tested**
extruded	C	PP	40 / 40	Tested	Tested	Tested	Tested
extruded	C	PP	30 / 30	Tested	-	Tested	Tested
extruded	C	PP	20 / 20	Tested	-	Tested	Tested
Woven	D	PET	35 / 35	-	-	Tested	Tested

* Chosen material for biaxial testing at University of Essen

† MD: unroll or machine direction of the product, CMD: cross-machine direction, perpendicular to MD

‡ specimen size: 100 to 200 mm square, overall size about 500 mm x 500 mm, min. 5 strips in both directions, strain rate: ~ 10 % / min.

§ stress (displacement) ratio for biaxial testing: MD / CMD = 1.0

Figures 6 and 7 provide first results of biaxial testing at the University of Essen as well as conventional wide-width tensile testing according to DIN EN ISO 10319 (1996).

For better identification of potential differences in the material behaviour due to its loading conditions it is preferable to plot the stiffness ratio R over the strain in place of conventional stress-strain curves, where $R = F_1\{\varepsilon\} / F_2\{\varepsilon\}$ and $F_1\{\varepsilon\}$, $F_2\{\varepsilon\}$ are measured forces of test 1 and 2 at a corresponding strain of ε. Assuming a stiffness ratio R equal to unity would illustrate that stress-strain curves generated in two different tests follow exactly the same pattern. A stiffness ratio R > 1 symbolises comparably stiffer, R < 1 softer material behaviour.

For further discussion it is important to note the nomenclature that has been defined to identify different testing combinations, Table 2.

Table 2. Nomenclature of CRS testing combinations

Test No.	Code	Principle loading direction of geogrid *	Type of testing equipment †	Type of loading
1	MD_E_biax	MD	Biaxial testing apparatus (Essen)	biaxial
2	MD_E_uniax	MD	Biaxial testing apparatus (Essen)	uniaxial ‡
3	MD_conv	MD	Conventional testing DIN EN ISO (10319)	uniaxial
4	CMD_E_biax	CMD	Biaxial testing apparatus (Essen)	biaxial
5	CMD_conv	CMD	Conventional testing DIN EN ISO (10319)	uniaxial
6 §	CMD_E_uniax	CMD	Biaxial testing apparatus (Essen)	uniaxial

* MD: Machine Direction (unroll direction), CMD Cross-machine direction

† E: University of Essen

‡ Note: uniaxial loading in the biaxial testing apparatus always includes the entire specimen and all clamps regardless whether only one direction is loaded!

§ Testing combination No. 6 has not been carried out

Figure 6 shows the stiffness ratio R for CRS testing in MD of the geogrid. The red line with squares is representing the stiffness ratio derived from biaxial and uniaxial testing in the biaxial apparatus at the University of Essen (MD_biaxE_biax / MD_biaxE_uniax). The red line marked with crosses is representing the stiffness ratio between biaxial testing in the biaxial testing apparatus and conventional wide-width tensile testing as per DIN EN ISO 10319 (MD_biaxE_biax / MD_conv).

One observes that R varies between both plots significantly for strains smaller than 1 %. When the strain increases to more than 1 % both lines are coming practically to the same, it seems that the variation of R is loosing relevance very fast. To explain the variation for small strains one should keep in mind that clamping effects as well as typical tolerances in the registration of strain and force are always very critical just at the beginning of a test. In regard of that it can be concluded that both equipments are behaving very similar, the modified clamping arrangement seems to provide the desired rotational flexibility to enable uniform stress distribution within the specimen. It is suggested that conventional testing can be taken as a reference for uniaxial loading conditions as long as readings for strains smaller than about 1 % are not considered.

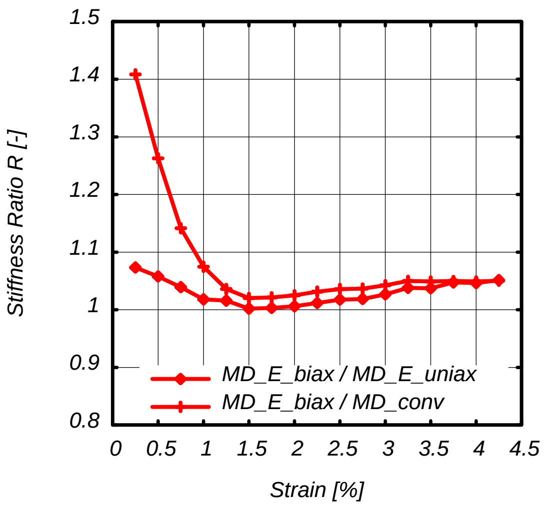

Figure 6. Stiffness ratio for MD derived from CRS testing at Univ. of Essen (biax. & uniax.) and conventional wide-width testing (DIN EN ISO 10319)

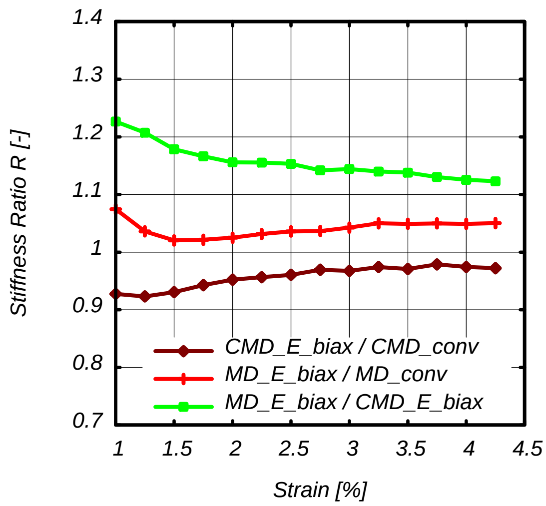

Figure 7. Stiffness ratio for MD and CMD derived from CRS testing at Univ. of Essen (biax. & uniax.) and conventional wide-width testing (DIN EN ISO 10319), stiffness variation of MD and CMD

Figure 7 shows a comparison of the stiffness ratio derived for MD and CMD of geogrid type B. As uniaxial testing in CMD has not been carried out in the biaxial testing equipment (CMD_biaxE_uniax) conventional testing was adopted to represent uniaxial loading conditions in this graph. The MD shows slightly stiffer material behaviour for biaxial loading conditions, R varies between 1.1 and 1.0, whereas CMD shows contrary behaviour. In that case R varies between 0,9 and 1,0 and indicates reduced stiffness for biaxial loading conditions. Since significantly different material behaviour cannot be concluded from these initial tests it would be appropriate to run a series of repetitions in order to evaluate standard deviation and confidence intervals.

The green line in Figure 7 shows the stiffness variation between MD and CMD derived from one single biaxial test. Unavoidable specimen variation is therefore excluded in this case. The stiffness ratio R (MD_biaxE_biax / CMD_biaxE_biax) is varying between 1.25 at 1 % strain and about 1.15 at 4 % strain. For strains less than 1 % R is varying between 1.65 at 0.25 % strain and 1.25 at 1 % strain (not visible in Figure 7 as readings for less than 1 % have been cut off for above mentioned reasons). In light of the above it is reasonable to conclude that the stiffness variation between MD and CMD within one production lot can be more important than differences that might be expected for a comparison between uniaxial and biaxial loading conditions.

Comparison with existing Data

Figure 8 shows stress strain curves for geogrid B published by McGown *et al.* (2004). Figure 9 shows the same results but adopting the format that was used for the analysis of the testing at University of Essen, see Figures 6 and 7. The stiffness ratio R varies for both geogrid directions, R_{MD} (MD_biax / MD_uniax) and R_{CMD} (CMD_biax / CMD_uniax), between 1.8 and 1.05. This indicates slightly stiffer material behaviour for biaxial loading conditions but a significantly higher variation is to be noted for MD than for CMD. This is not logic as the stiffness variation between MD and CMD for biaxial testing (MD_biax / CMD_biax) is marginal, MD and CMD are very homogeneous in this case.

The variation of the stiffness ratios observed from Kupec et al. is most likely caused by the loading and clamping arrangement and not a consequence of the loading conditions.

In regard of above it is suggested that no potential stiffening effect should be concluded from CRS-testing of this geogrid.

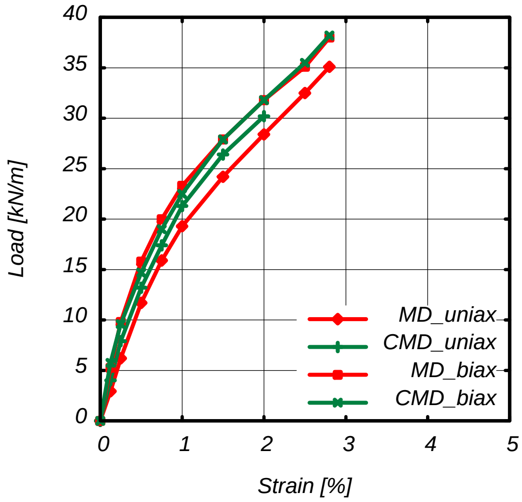

Figure 8. Stress-Strain Curves for Uni- and biaxial CRS testing Kupec (2004) and McGown *et al.* (2004)

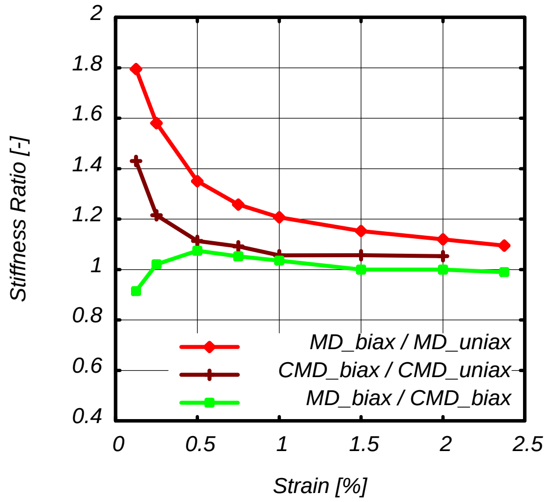

Figure 9. Stiffness ratio for MD and CMD derived from CRS testing at Univ. of Strathclyde, see Figure 8

Conclusion from initial CRS-testing

Comparison of conventional as well as uni- and biaxial CRS-testing in a biaxial testing apparatus showed that:

- Loading and clamping conditions adopted in the testing apparatus of University of Essen enables appropriate biaxial testing of geogrids
- Variation of material stiffness for MD and CMD within a single product seems to be more relevant than a potential stiffening due to biaxial loading conditions
- Significantly different material behaviour (stiffening) as a result of biaxial loading cannot be verified for the PET welded geogrid tested.

In light of above it was decided to stop CRS testing at this level and to focus on sustained loading tests only.

BIAXIAL SUSTAINED LOADING TEST - CREEP TESTING

Sustained loading tests are carried out in order to investigate the time dependent deformation behaviour of the material. Heerten et al. (2005) published that the welded PET geogrid (type B in table 1) shows significantly reduced creep behaviour when loaded biaxially. It was observed that there is a time shift of 1x104 h between uniaxial and biaxial loading, for a stress ratio of 50 %, for a stress ratio of 30 % even 1x105 h to reach the same strain level.

In order to verify this substantially improved material behaviour it was decided to continue testing at the University of Essen performing uni- and biaxial sustained loading tests.

Table 3 shows the identification for sustained loading tests given in the following plots.

Table 3. Sustained loading tests

Test No.	Code	Principle loading direction of geogrid *	Type of biaxial testing equipment †	Type of loading	Remark
1	MD_E_biax	MD	Essen	biaxial	
2	CMD_E_biax	CMD	Essen	biaxial	
3	CMD_E_uniax	CMD	Essen	uniaxial ‡	
4	CMD_S_biax	CMD	Strathclyde / Aachen	biaxial	
5	CMD_S_uniax	CMD	Strathclyde / Aachen	uniaxial	
6	CMD_S_biax_RH	CMD	Strathclyde / Aachen	biaxial	Ramp and Hold
7	CMD_S_uniax_RH	CMD	Strathclyde / Aachen	uniaxial	Ramp and Hold

* MD: Machine Direction (unroll direction), CMD Cross-machine direction
† E: University of Essen, S: University of Strathclyde / RWTH-Aachen
‡ Note: uniaxial loading in the biaxial testing apparatus at Essen always includes the entire specimen and all clamps regardless whether only one direction is loaded!

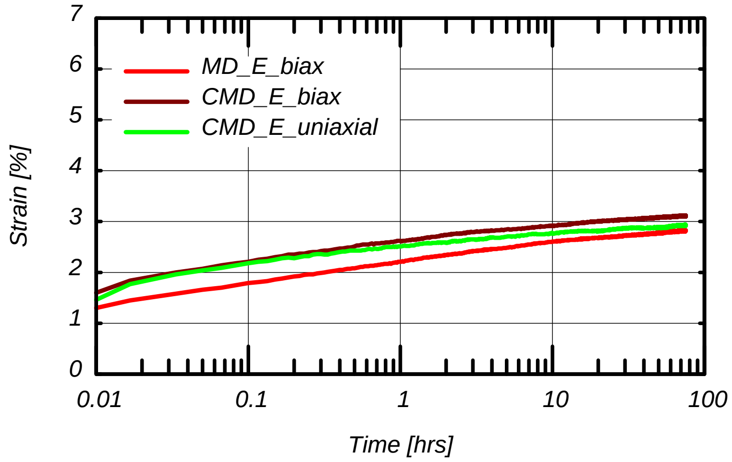

Figure 10. Sustained loading tests at University of Essen, grid type B

Figure 10 shows results of biaxial and uniaxial creep tests of geogrid type B in Table 1. The stress ratio was set to 50% of the nominal strength (corresponding to 30 kN/m) to allow for direct comparison of the test results. Testing equipment, loading and clamping arrangement for this long term testing was the same as for CRS testing described above. It is obvious that there is nearly no difference in the creep behaviour regardless of the loading conditions. The time vs. elongation plots for CMD_E_biax and CMD_E_uniax are matching almost perfectly. Small differences can be noted between MD_E_biax and CMD_E_biax, however the inclination of the creep-curve is still nearly the same. Since these results do not match at all with the conclusions of Heerten *et al.* (2005) the problem was analysed in depth to find the reasons for this discrepancy.

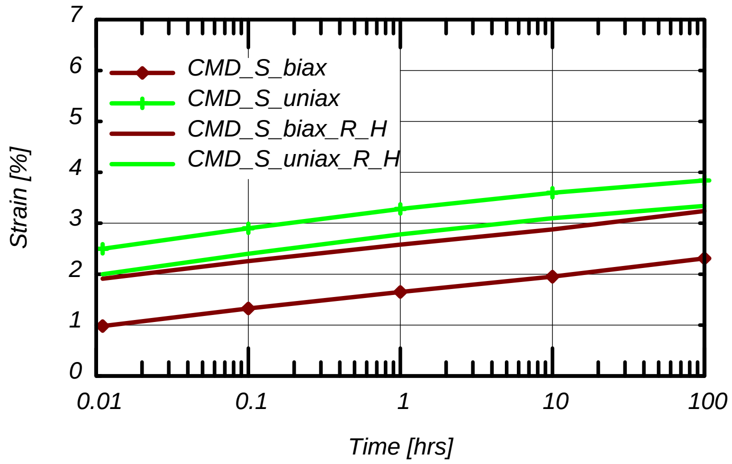

Figure 11. Sustained loading tests at University of Strathclyde, Modification with Ramp – Hold, CMD, grid type B

Figure 11 shows results of sustained load testing at a stress level of 50 % for geogrid type B published from Heerten *et al.* (2005). It is obvious that the plots for uni- and biaxial loading conditions are running parallel with the same gradient, shifted only by a constant value of strain of roughly 2 %. This means that the creep behaviour as such does not differ depending on the loading conditions.

Thornton *et al.* (1999) have shown that so called ramp and hold short term creep testing can be helpful to eliminate the effect of variation in the strain response of long term creep testing and to insure compatibility of the strain relationship between short term and long term testing. The green and brown lines without signature in Figure 11 show an adaptation of this concept to the test results of Kupec. As additional ramp and hold testing could not be performed it was decided to use the results of the CRS testing (compare Figure 8) for a first approximation. For the stress ratio of 50 %, corresponding to 30 kN/m, figure 8 reads about 1.9 % strain for biaxial loading and 2.0 % for uniaxial loading. Figure 11 shows clearly how the creep curves get shifted if these values are adopted to represent the initial strain. There is no difference to be noted anymore between the creep strain for biaxial and uniaxial loading.

Figure 12 shows the modified creep curves in the same plot with creep test results received from testing at University of Essen: all four plots have virtually the same inclination.

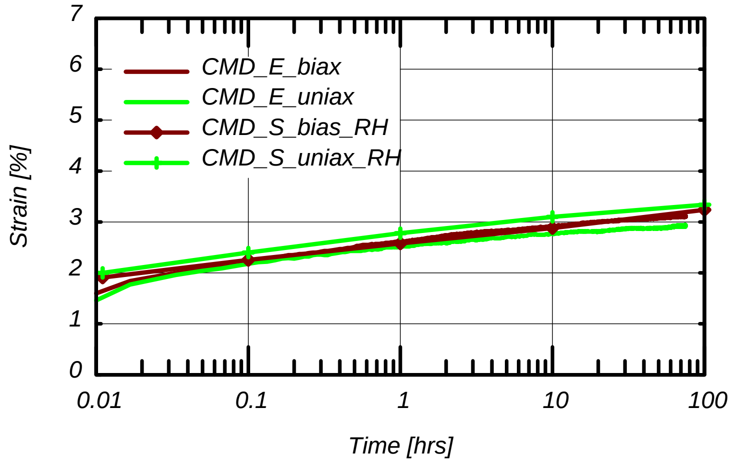

Figure 12. Sustained loading tests at University of Strathclyde, Modification with Ramp – Hold, and University of Essen, CMD, grid type B

Above findings give reason to suggest that problems related to the loading and clamping arrangement of the testing apparatus at the University of Strathclyde have caused the initial shift in the strain. As this would be a variation imminent for the equipment and the method generally and not specific for a single product it should be obvious in the results of other testing also.

Table 4 shows the comparison of the initial strains generated in CRS-testing and creep testing, for geogrid types A, B and C as published from Kupec (2004).

Table 4. Compilation of initial strains for biaxial testing at University of Strathclyde

Geogrid Type	Initial Strain in MD, stress ratio 30% of nominal strength [%]			
	CRS-testing		Sustained load testing	
	uniaxial	biaxial	uniaxial	biaxial
A	1,75	1,75	1,37	0,96
B	0,8	0,75	1,25	0,33
C	2,3	2,1	1,05	0,54

Conclusion from analysis of sustained loading - testing

Comparison of mono- and biaxial creep-testing in the biaxial testing apparatus at University of Essen showed:

- Similar creep behaviour of the PET welded geogrid tested regardless of the loading arrangement (uniaxial / biaxial)
- Significantly different results than were found from Kupec (2004) and Heerten *et al.* (2005)

Analysis of the test results of University of Strathclyde showed:

- Significant variation of initial strains but similar creep behaviour
- Similar creep behaviour regardless of the loading arrangement (uniaxial / biaxial) after a CRS-testing based shifting
- Good correlation between shifted creep-curves and test results at University of Essen

SUMMARY AND CONCLUSION

Detailed knowledge about biaxial testing of geogrids is limited to date, elaborate testing has been reported only by Kupec (2004) and McGown *et al.* (2004).

Analysis of the available information suggests that boundary conditions of the testing equipment especially the clamping and loading arrangement may have caused misinterpretation of the mechanical behaviour under biaxial stress conditions.

Additional testing at University of Essen was carried out in order to provide a basis for comparison and verification of the actual information. Significantly improved loading arrangement and specially designed single strip clamping was available there. It was found that the substantial differences in the material behaviour reported by others cannot be verified for the tested geogrid from welded PET strips neither in short term (CRS-testing) nor in sustained loading tests. The production technology, especially the formation of the crosspoints between the reinforcement elements of the longitudinal direction (MD) and the cross direction (CMD) of a geogrid, which was declared to be the basic reason for a potential stiffening effect under biaxial loading seems to be without any importance in that regard. The derivation of reduced partial reduction factors for creep rupture and biaxial loading conditions, as was published by Heerten *et al.* (2005), needs careful revision.

Significant variation of the initial modulus observed for the testing carried out at the University of Strathclyde so far gives reason to assume that the same conclusion can be drawn for other geogrid types also, regardless of the raw material and the formation of the cross points. Additional testing is required to verify this assumption.

Important conclusions about the load transfer mechanism of geogrids in reinforced soil structures that have been based on findings by Kupec et al. may need careful revision.

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