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Postprint

This is the accepted version of a paper published in *Journal of Sandwich Structures and Materials*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Rajput, M S., Burman, M., Köll, J., Hallström, S. (2017)

Compression of structural foam materials: Experimental and numerical assessment of test procedure and specimen size effects

Journal of Sandwich Structures and Materials

<https://doi.org/10.1177/1099636217690500>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-203868>

Compression of structural foam materials – experimental and numerical assessment of test procedure and specimen size effects

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Abstract

This study was initiated based on the observation that standardized test methods for flatwise compression of foam materials give significantly different test results for the measured moduli, and that these standards to date lack adequate instructions on how the strain should be measured and what specimen size should be used. A brief review of previous work shows that existing test methodologies provide significantly different results for the compressive moduli of foams depending on how the strains are measured. A thorough experimental study of the out-of-plane compressive properties is conducted on three different closed cell foam materials, where strains measured with two different extensometer placements, and with digital image correlation, come out significantly differently. A parametric study is also performed showing that the results vary considerably with in-plane specimen dimensions, indicating effects of finite size and localized strain at edges. Both stochastic amorphous and homogenized finite element models of foam back the experimental observations by illustrating effects of finite size and various boundary conditions on the measured properties.

Keywords

Cellular, Polymer, Material Characterization, Test Method, Compressive modulus, Poisson's ratio,

1 Introduction

Sandwich structures are widely employed as lightweight solutions in aerospace, marine, automotive and civil engineering applications. They are constituted by bonding stiff and strong face materials to low-density core materials which are usually made of foams, honeycombs or balsa wood. The focus in this work is on closed cell structural polymer foams.

With increased use of sandwich structures, good understanding about the mechanical behavior of its constituents is indispensable and the microstructure, mechanics, crush mechanisms and general behavior of foams are thoroughly described in the literature [1–4]. One key parameter of a sandwich core material is its out-of-plane compressive properties. Accurate quantitative data of such properties are crucial for modeling and analysis of sandwich design and also the impact response [5–8].

Flatwise compressive properties of polymeric foam core material have previously been investigated by many researchers [9–16], but no comprehensive evaluation of the test methodologies have been performed. Benderly et al. [11] focused on a shear/compression failure criteria for Rohacell 200WF core material and suggested some modifications to the test standards for the evaluation of the shear strength. Oulette et al. [13] studied foam compressive properties at various strain rates. Flores-Johnson et al. [14] explored the elastic modulus degradation during progressive crushing of foam cores under uniaxial compression with focus on the reduction of the elastic modulus within the plateau region, i.e. for strains beyond the elastic range. Arezoo et al. [15] studied the mechanical response of foam material of different densities in order to map the deformation mechanism at different length scales whereas Koissin et al. [17] compared the response of pre-crushed foam material under uniaxial compression, tension and shear with that of the virgin foam material.

As part of a damage tolerance assessment study of sandwich structures, flatwise compression tests of foam core materials are performed. Some lack of coincidence is found in the literature and the test standards [18,19] also suggest slightly different procedures for evaluation of compressive properties. This motivates a thorough review of the established test methodologies, related test setups and the result evaluation. To the knowledge of the authors no previous study has reviewed existing test methods and their recommended result evaluation for flatwise compression of foam materials subjected to quasi-static compression.

2 Experimental Study

2.1 Material system and specimen data

In the present study three closed cell structural foams commonly used as core materials in sandwich structures are investigated; Rohacell 200 Hero, a Polymethacrylimide (PMI) foam supplied by Evonic AG; ArmaFORM AC115, a Polyethylene terephthalate (PET) foam supplied by Armacell SA; and Divinycell H60, a crosslinked polyurea/polyvinyl chloride (IPN) foam supplied by DIAB AB. The chosen materials are made of three different polymers and they also differ in density and (average) cell size. Microscopy images of Rohacell 200 Hero and Divinycell H60 were presented in [20] and an image of ArmaFORM AC115 is shown in Figure 1. They are also produced in well-established processes, providing relatively low variation in properties. The three foams are in the following referred to as R200H, AC115 and DH60, respectively and their mechanical properties, as given by their manufacturers, are presented in Table 1. The different tests are presented more thoroughly in the following and details of the test matrix are provided in Table 2.

Four different test configurations are used as outlined in Table 2. From the first, the compressive properties of all three foam materials are evaluated. Then the R200H and the DH60 materials are tested after being primed and finally the R200H material is also tested in sandwich and bonded configurations. All tests are presented in greater detail in the following sections.

In the sandwich test configuration, uni-directional (UD) carbon fiber laminates (HTS40-242 g/m²) are used as face sheets. The sandwich materials are manufactured in-house using a vacuum infusion process with vinylester (DION 9102) resin. The face sheet thickness is 2.5 mm.

Table 1. Nomenclature and manufacturers' data for the foam materials

Material	Foam alias	Nominal density [kg/m ³]	Comp. strength [MPa]	Comp. modulus [MPa]	Tensile modulus [MPa]	Shear modulus [MPa]
ArmaFORM AC115	AC115	115	1.8	120/80*	120	30
Divinycell H60	DH60	60	0.9	70	75	20
Rohacell 200 Hero	R200H	205	7.1	180	389	109

*Values from two different test methods are provided

Table 2. Test matrix for the current study

Configuration	Foam	Core thickness [mm]	No. of samples	Sample size [mm x mm]
Pure foam	R200H	20	5	50 x 50
	DH60	50	5	50 x 50
	AC115	50	5	100 x 100
Primed foam	R200H-P	20	5	50 x 50
	DH60-P	50	5	50 x 50
Sandwich	R200H-S	20	5	30 x 30
Bonded	R200H-B	20	5	50 x 50

Figure 1. Microscopy of ArmaFORM AC115

2.2 Experimental setup

The test setup is shown in Figure 2. Two screw-driven universal test machines are used in the tests, one with a 100 kN load cell (Instron 4505) and the other with a 30 kN load cell (Instron 5567), depending on the load levels. Two rigid 200 mm diameter steel platens are mounted to the fixture and shimmed to perfect alignment, minimizing the risk of non-uniform stress over the loaded surfaces. Two ASTM standard test methods are followed in this study; ASTM D1621 [18] and ASTM C365/365M [19]. These are the most established test standards found in the literature for flatwise compressive tests of foam materials, e.g. [10,11,13,21–23]. The force and the displacement of the crosshead are recorded by a computer system connected to the test machine as per the recommendation in the standards. In addition one extensometer (Instron 200873), denoted Ext.1, is used for direct measurement of the platen displacement. A second extensometer (Instron 205210), denoted Ext.2, is applied to measure the strain directly on the foam material. The tests are performed at constant crosshead displacement rates set to 10% of the specimen's original thickness per minute to assure quasi-static loading conditions. All tests are performed at $23\pm2^\circ\text{C}$ and $50\pm2\%$ relative humidity.

Figure 2. Setup for the out-of-plane compression tests.

2.3 Out-of-plane compression

A typical stress-strain curve from a quasi-static compression test of a structural polymeric foam material (R200H) is shown in Figure 3. After an initial toe on the curve, related to seating of the specimen, three distinct regimes representing principally different mechanical response can be seen in the stress vs. strain curve.

In the initial elastic regime, the material response is virtually linearly elastic (up to 3-4% strain in Figure 3) and then, close to the yield point, the elastic response ends.

The first significant deviation from the linear regime constitutes the onset of the crushing regime where a relatively constant plateau stress is observed, representing progressive crushing from collapse, buckling and plausible breaking of cell walls and/or formation of plastic hinges at cell wall junctions [1] (The event is typically non-uniform and the engineering stress-strain relation after yield should thus be used with care when making conclusions about the true material behavior.)

When all cells have collapsed the crushed material starts to pack and lock up, which defines the densification regime of the foam, where the apparent compressive stress increases drastically and progressively with increasing strain.

Since the present study is focused on the estimation of the compressive modulus, and to some extent also the yield strength, the presented tests and evaluations concern the material behavior up to and slightly beyond the point of yield, i.e. primarily the elastic regime of the materials.

Figure 3. A typical compressive engineering stress vs. engineering strain curve for a structural polymer foam.

2.4 Initial compression tests

Strain measurements based on readings of the test machine's crosshead displacement are not considered in this study since such are known to be uncertain due to compliance of the machine and the test rig. The displacement is instead obtained from two extensometers. One extensometer (Ext.1) is mounted between the two load platens. A second extensometer (Ext.2) is mounted directly onto the foam material. The strain reading from Ext.1, corresponding to the true machine displacement, is referred to as “*gross strain*”, whereas the reading based on Ext.2 is denoted “*net strain*”.

For the R200H and the DH60 materials parallel readings of the strains are also made with digital speckle photography (DSP) analysis [24]. DSP allows for more detailed readings of the strains than extensometers since it provides full field data over the surface viewed by the camera. The speckle pattern is carefully applied onto the observed area enabling the DSP to track the movement of the material surface precisely. The DSP system ARAMIS 6.3 from GOM GmbH is used in this study. Strains from the DSP system are obtained by selecting an area over the exposed foam surface, which gives an average estimate of the strain. It should be noted that the DSP system is incapable of resolving strains in regions where the speckle pattern is severely distorted, a problem that tends to occur in the very vicinity of the loading platens.

Stress versus strain results from flat-wise compression tests of the three different foam materials are presented in Figure 4, where the moduli are p by thin lines. The difference between the *gross* and *net strain* is striking. For two of the materials it is greater than a factor of two. Notably there is not only a long toe at the beginning of the curve from Ext.1, addressed in the ASTM C365/365M standard [19], but the whole response differs significantly. The results from the DSP correlate almost exactly with the *net strain* results, indicating that they are the ones to trust. The fact that the results are similar for all the tested materials indicates that the difference likely to come from the test methodology. The detailed results are presented in Table 3.

Figure 4. Uniaxial compression results using two different extensometer placements and DSP analysis. (a) Rohacell 200 Hero, (b) Divinycell H60 and (c) ArmaFORM PET AC115

Table 3. Compressive modulus measurement results

Foam material	Compressive modulus		
	Ext.1 [MPa]	Ext.2 [MPa]	DSP [MPa]
R200H	277 ±26	405 ±38	413 ±10
DH60	39 ±10	70 ±8	74 ±12
AC115	68 ±4.4	139 ±6.6	—

It can be seen in Figure 4 that the *net strain* readings from Ext.2 are linear almost from the start of the tests and the modulus is derived from this linear regime, in the range 0.1-0.5% strain. For the *gross strain* recordings from

Ext.1 the response is initially clearly non-linear and the modulus is then extracted at the maximum slope of the curve. In spite of that, the modulus results come out much lower than when the *net strain* is used. A sensitivity study was performed to check for variations in modulus as function of selected data points from the recordings showing that 30 consecutive data points used in the evaluation provided robust results for the modulus calculations.

The difference in modulus from the two extensometers is consistent for all three materials although they have different thickness, cell size, density and specimen dimensions, indicating that the result is systematic and not material-specific. The difference arises from the fact that the extensometer between the steel platens measures higher strains than the extensometer mounted on the foam material. The test standards at hand [18,19] do not specify how the strains should be measured, which implying that very different test results could be obtained for the same material.

2.4.1 Previous measurements

The findings above suggest that there should be inconsistent results from previous published studies and in fact there are significant modulus differences reported for polymeric foam materials in the literature, here only referring to a few studies that relatively easily can be assessed in the light of the current work.

Li et al. [10] studied the mechanical behavior of Rohacell 51WF foam using the ASTM C365/365M test standard [19] and evaluating the *gross strain*, which provided very low modulus results. Li et al. attributed this to uncompensated crosshead displacement or seating effects. Similar results for Rohacell 51WF foam were reported in work by Flores-Johnson [14], where a study of elastic modulus degradation was conducted without addressing the possible difference in the measured elastic moduli. Arezoo et al. [15] performed quasi-static experiments on four different densities of Rohacell WF foam material, and a contact-free laser extensometer was used to measure the compressive *gross strain* and a slightly higher compressive modulus than in [10] was reported. Another study of the same foam material was performed by Zenkert et al. [8] using the *net strain* in modulus measurements, which resulted in considerably higher modulus results. The mentioned results are summarized in Table 4.

In addition, Schwingshackl et al. [25] performed an extensive overview of the use of experimental and analytical methods for the determination of orthotropic material properties of honeycomb core materials. The ASTM C365/365M test standard [19] was followed, again leading to a low modulus value compared to other approaches, although the authors attributed this difference to geometry inaccuracies or cell imperfection of the test specimen. Nonetheless the study highlights that honeycomb core materials are also sensitive to differences in test methodologies.

Table 4. Comparison of elastic modulus values from previous studies

Foam material	Previous studies	Strain measurement	Compressive modulus [MPa]
Rohacell 51WF	Li et al. [10]	Gross strain	22
	Flores-Johnson et al. [14]		
	Arezoo et al. [15]	Gross strain	32.5
	Zenkert et al. [8]	Net strain	75

2.5 Complementary compression tests

There are several plausible reasons for the difference in strain readings from the two locations of extensometers. It could be due to the presence of open and/or damaged cells at the cut surfaces of the foam material, which would then cause a locally more compliant response. Another possible reason is un-even stress distribution occurring at the loaded surfaces due to skew or in-homogenous load introduction to the specimens. In order

to identify the source of the deviation complementary studies are performed, focusing primarily on the Rohacell 200 Hero material.

2.5.1 Primed specimens

The effect of damaged cells at the loaded surfaces is investigated by applying a thin layer of vinyl ester resin (Dion 9102) on both faces of blocks of R200H and DH60 foam, intending to stabilize open/damaged cells by filling and stiffening them. The resin is applied with a brush on one side of the blocks at a time and they are then left to cure at room temperature overnight. Samples of in-plane size 50x50 mm are finally cut from the primed core blocks using a band saw.

Out-of-plane compression tests are performed on the primed specimens according to the mentioned test setup and the results are presented in Figure 5 and Table 5. For the R200H material little difference is found for the stress vs. *gross strain* response compared to the case without priming while for the DH60 material the apparent stiffness is about 20% higher after priming. It was previously suggested by the authors [20] that foams with larger cells, the DH60 foam in this case, are more susceptible to the effects from priming since the resin can easily saturate and fill their open cells at the cut surfaces. The initial toe in the stress/strain curves is somewhat reduced for both materials.

Figure 5. Comparison of gross strain results with and without priming (a) R200H-P and (b) DH60-P. The net strain is also shown as reference

Apparently the difference between the *net* and *gross strain* still remains after priming the loaded surfaces of the R200H material and it decreases only partly (about 1/3) for the DH60 material.

2.5.2 Sandwich specimens

Compression tests of sandwich specimens are also performed in order to evaluate the difference in strain measurements. The load is then applied onto the sandwich face sheets and thus by-passing the direct contact between the foam and the load platens. Details of the sandwich specimens are presented in Table 2. Stress vs. strain curves and the results from the compression tests are presented in Figure 6 and Table 5.

Figure 6. Engineering stress-strain curves for sandwich specimens (R200H-S) based on two physical extensometer locations and DSP results

The *gross strain* results indicate a slightly higher stiffness compared to the results from the pure foam specimens (see Table 3 and Table 5) while the *net strain* (Ext.2) results are unaffected. The modulus derived from the *net strain* is still 30% higher than that derived from the *gross strain*. The *gross strain* is in this case evaluated as the displacement from the extensometer (attached to the load platens) divided by the foam core thickness thus assuming that the face sheets have infinite out-of-plane stiffness. The low modulus result from the *gross strain* indicates that there is deformation somewhere else than in the foam, likely where the specimen's face sheets are in contact with the load platens.

2.5.3 DSP analysis

For better understanding of the differences, strain recordings using digital speckle photography (DSP) analysis is employed in addition to the extensometer readings. To accommodate better resolution from the DSP analysis near the loaded surfaces of the foam, a random speckle pattern is applied on the load platens as well. There are still some obvious problems to read out the strains accurately, partly due to the localized high strains as such and partly due to the material interfaces and the load platens being located closer to the camera than the foam material. It is however deemed reasonable to rely in the overall trends from the DSP results. Since the spotted differences are in the order of magnitude even relatively large errors are of less concern for the overall results and their phenomenological interpretations.

Complete strain field results for pure R200H material are presented in Figure 7, showing that the strain is an order of magnitude higher near the loading platens, while much lower and seemingly uniform strain is observed in the rest of the foam material. Note that this relative difference occurs already at relatively low load levels, well within the elastic regime of the material, and it is thus not associated with crushing of the foam.

Apart from plots showing the full strain field, as the one given in Figure 7, strains are also evaluated along three virtual lines in the specimen, one centered and two peripheral, indicated by C, P1 and P2, respectively, in Figure 7. The through-thickness transverse strain variation for the central section of the specimen (C in Figure 7) is shown in Figure 8. The strain concentrations seen for the case of pure foam, could explain the difference between the *net* and *gross strain* measurements. In the sandwich specimen the strain is similar to that in the foam specimen but without the strain peaks at the top and bottom surfaces.

Figure 7. Images showing the vertical strain ϵ_y according to the DSP (foam material only) indicating 3-4 times higher strain levels locally, near the load platens, than in the middle of the specimen.

Figure 8. The vertical strain variation through the thickness of three different specimen types; R200H, R200H-S and R200H-B. The strains are extracted in the elastic regime, along a path at the center of the specimen (C in Figure 7).

The through-thickness variation of the in-plane (transverse) strain ϵ_{xx} is also studied along the three different vertical lines indicated in Figure 7. The strain distributions at two different load stages are plotted in Figure 9(a). Apart from the obvious fact that the in-plane strain increases with the load the plots also show that the highest strains are found in the middle of the sample. In the linear regime, the strain variation is small at the middle part of the specimen, and appears to be zero at the load platens. The latter indicates that there is significant friction on the loaded surfaces but could also be an artifact from the DSP software interpolating the strain with that of the neighboring steel platens, which is virtually zero. The variation of the in-plane strain ϵ_{xx} within the linear regime at these sections is plotted in Figure 9(b), and no significant difference is visible between the three different sections. If, on the other hand, the deformation of the three sections is studied, see Figure 10, there is a significant difference. Greater in-plane displacements in the peripheral parts (P1 and P2) are visible which correspond to bulging of the vertical surfaces of the specimen. Another interesting observation is that the centered section (C) shows a slight slope, which might indicate that there is also shear deformation in the foam material, due to the applied compression. In fact the deformation curves for the two peripheral reference lines (P1 and P2) show similar sloping trends, apart from the more pronounced bulging deformation, which supports that the material is also shearing slightly.

The results from the DSP analysis is also used to estimate the Poisson's ratio. It is also derived from the ratio between strains from the two virtual extensometers measuring the horizontal and vertical strain, within the

elastic regime. Some minor variation occurs but the result comes out in the range of 0.29-0.33. The manufacturers of the tested foams do not provide the Poisson's ratio in their data sheets and if it is back-calculated from their presented tensile and shear moduli it comes out unrealistically high – far above 0.5. This discrepancy is also highlighted by Li et.al [10] for Rohacell-51 WF structural foam material.

Figure 9. Through-thickness variation of the horizontal strain ϵ_{xx} for R200H (a) at P1 for two different load levels and (b) along P1, C and P2 at the lower load level. (P1, C and P2 are indicated in Figure 7).

Figure 10. Variation of the horizontal displacement through the thickness within the elastic regime of the R200H foam. (P1, C and P2 are indicated in Figure 7).

Similar DSP analysis is performed for the sandwich configuration and a map of the transverse strain is shown in Figure 11. High localized strain is indicated in this case too but now between the sandwich face sheets and the machine's load platens. It is also more pronounced for the lower than the upper face sheet in the figure. It is believed that the asymmetry originates from the sandwich manufacturing process, where one side of the sandwich material rests on a perfectly flat table while the other is controlled only by a vacuum bag, where a peel ply also gives a certain dimpled imprint on the surface.

The vertical strain variation is plotted in Figure 8 where it can there be compared with corresponding strain distribution for the pure foam configuration. As seen there are no significant local strain peaks present in the foam when tested in a sandwich specimen. The engineering stress vs. strain curves from Ext.1 and Ext.2 are

also compared with a virtual extensometer from the DSP (see Figure 6), applied over the foam, and again the DSP results agree well with the *net strain*.

Figure 11. Vertical strain maps from the DSP for the R200H sandwich case.

The fact that one outer face of the sandwich specimen is flat and smooth (the top surface in Figure 11) should make the stress distribution and, consequently, the strain relatively even in that face sheet. Minor deviations could possibly occur due to friction on the loaded surfaces, preventing in-plane expansion but that would then decrease the local strains rather than the opposite, and the difference in magnitude should also be much smaller. Similarly the DSP indicate bands of higher strain at the core to face sheet interfaces and there is no apparent reason for that. Since the core surfaces are co-impregnated together with the face sheets under vacuum during the manufacturing process, the interfaces are probably stiffer than the neighboring foam material. The elevated strain levels are thus more likely due to poor strain resolution near the bi-material core to face interface.

Given the above, the higher strains at the top interface in Figure 11 are believed to be artifacts from the DSP evaluation due to poor resolution in the proximity to the loading platens, while the higher localized strains at the bottom face are believed to partly be true but somewhat exaggerated due to the proximity to the other loading platen. The argument for this is that no other specimen configuration than the sandwich case shows such pronounced asymmetry and the sandwich specimen is locally asymmetric in a way that could explain the result.

A hypothesis based on the DSP analysis is that the high strains at the specimen boundaries come from local effects at the loaded surfaces that in turn originate from the non-smooth contact between the specimens and the load platens. Since the load is introduced on a non-smooth surface, high localized stresses occur at the interface resulting in correspondingly high local strains.

If the loaded surfaces are included in the strain measurements any attempt to extract reliable homogenized material data from compressive testing will be impeded. The error is most pronounced when the load is applied directly onto the foam material, due to its inhomogeneous cellular morphology. However it occurs to a significant extent also when the foam is sandwiched between two face sheets, and it seems to be worse if the outer face surfaces are not perfectly smooth.

The high local strains contribute to an underestimated measured compressive modulus if an extensometer is mounted between the loading platens. Applying the extensometer directly onto the foam material and thereby evaluating the *net strain*, i.e. only the strain in the interior part of the specimen, eliminates this source of error.

2.5.4 Bonded specimens

In order to verify the above hypothesis yet a set of experiments are conducted where R200H foam material is bonded directly onto load platens using an epoxy adhesive. The bonding is made by applying an extra pair of steel plates between the machine's load platens and the foam, and then bond the foam to the extra plates using the test machine and its platens as a fixture. The *gross strain* extensometer (Ext.1) is then applied between the extra steel plates during the tests. The setup is aimed to eliminate potential localized uneven loading.

The moduli extracted from Ext.1, Ext.2 and the DSP are listed in Table 5, and the stress-strain curve from one of the sample is shown in Figure 12. For the bonded case the modulus from Ext.1 comes out very similarly to that from Ext.2. The result is also in line with results from Koissin et al. [16] who tested Rohacell 51WF foam material in cyclic compression-tension loading, following the ASTM 1623-78 standard [26] They evaluated the *gross strain* with the specimens bonded to the loading blocks and reported a modulus of 85 MPa which is actually even higher than the one extracted from the *net strain* by Zenkert et al. [8], see Table 4.

The strain map from the DSP is presented in Figure 13 where no higher strains are present at the load interface compared to the rest of the cases, but there are small traces of locally higher strains near the load plate interfaces. The small spots indicating higher strain are most likely local effects on the exposed surface, associated with excess epoxy running out from the joint between the spots and the plates – areas with zero strain (blue) in the plot – compressing the neighboring material on the surface relatively more.

It should again be noted that measuring strains near the foam-plate interface is inherently difficult. It is however clear that the peak values found for the pure foam case are not only an artifact from the DSP, since it is not seen at all for the bonded case (see Figure 8).

Figure 12. Engineering stress-strain curves from two extensometers and DSP on a bonded specimen.

Figure 13. Vertical strain maps from the DSP for the R200H bonded case.

Table 5. Compressive modulus measurements from different tests

Test case	Compressive modulus [MPa]		
	Ext.1	Ext.2	DSP
R200H	277 ±26	405 ±38	413 ±10
R200H-P	279 ±15	410 ±24	-
R200H-S	301 ±20	404 ±25	392 ±19
R200H-B	396 ±18	405 ±12	408±15
DH60	39 ±10	70 ±8	74 ±12
DH60-P	51 ±7	72 ±9	-

3 Parametric study

In addition to the assessment of the test methods for determining the flatwise compressive properties of polymer foam materials, it is also essential to investigate the effect on the measured compressive properties related to specimen size and other geometrical parameters. This study includes the effect of specimen shape (cylindrical vs. block) and the effect of size (thickness to cross sectional area and cell vs. specimen volume). All test specimens are cut using a band saw and then trimmed to precise final dimensions with a sanding machine. The cross section area of the cylindrical specimens is selected to be equivalent to that of the block samples for comparison purposes. The different sample shapes and sizes are presented in Figure 14.

Figure 14. Rohacell 200 Hero cross section types, (a) block and (b) cylindrical.

It turns out that the in-plane size variation has a significant influence on the compressive modulus but no influence on the compressive strength (not shown here). This former is illustrated in Figure 15 (and corresponding modulus value in Table 6) where the normalized compressive modulus from the *net strain* is plotted versus the ratio between the specimen thickness and its normalized width. In terms of specimen thickness-to-width ratio the modulus appears to converge when the thickness equals or exceeds the specimen width. For greater in-plane specimen size (versus thickness) the measured modulus increases, likely due to friction on the loaded surfaces that causes deviation from plane stress towards plane strain, and accordingly higher stiffness. This conclusion is more substantiated by numerical analysis presented in a later section.

The conclusion above means that most of the results presented in the previous section are believed to overestimate the true compressive modulus slightly. Note however that it is not clear that the measured compressive modulus should come out identical with the tensile modulus given by the manufacturers, since the former is measured out-of-plane while the latter is measured in-plane. Some foam materials show variations of material properties through the thickness and a slight anisotropy related to conditions during the foaming process is also common. Elongations of cells due to such conditions is for instance clearly visible in Figure 1.

There is no statistically certified difference between the results from the specimens with square and circular cross section areas (see Figure 15) but the cylindrical specimens consistently show slightly higher average modulus results. It might be pure coincidence but could also indicate that a circular cross section due to its axisymmetry is slightly more prone to build up tractions to the load platens. The circular cross section also implies a slightly smaller (about 11%) circumference. Assuming that presence of cut cells on the free surfaces would decrease the measured stiffness somewhat, specimens with circular cross sections can be expected to show slightly higher stiffness than specimens with similar but square cross section areas. These effects can however neither be confirmed nor entirely ruled out from the tests. If they exist they seem to be in the order of 5% for the R200H material. The influence of edge effects was not addressed specifically in the experiments but examined with numerical simulations, which is discussed more in the following section.

Figure 15. Normalized modulus for varying cross section area and sample types.

Table 6. Compressive modulus of R200H and DH60 from net strain for different specimen shapes and sizes

Material	Cross section area [mm ²]	100	625	2500	5625	10000	15625
R200H	Block specimens	358±13	367 ±22	405 ±38	429 ±40	431 ±38	-
	Cylindrical specimens	-	385 ±40	435 ±49	-	454 ± 48	-
DH60	Block specimens	-	71±13	74±12	-	-	79.5±3.5

4 Finite element modeling

A finite element (FE) study is performed to validate the experimental observations using both homogenized and stochastic amorphous foam models.

4.1.1 Homogenous model – study of size effects

Two 3D FE models of specimens with square and circular cross sections are first generated using ABAQUS [27]. 20-noded quadratic brick elements (C3D20) are used and examples of the models are displayed in Figure 16. In the initial FE study the material is treated as linearly elastic, homogenous and isotropic with a Young's modulus of 400 MPa and a Poisson's ratio of either 0.3 or 0.4, where the former is similar to the modulus derived from the experiments with specimen having 50 x 50 mm square cross section areas. All degrees of freedom at the bottom surface are constrained and a prescribed vertical displacement is applied at the top surface while keeping the two in-plane degrees of freedom on the loaded surface constrained. A parametric study is performed where the in-plane size is varied while keeping the thickness $t=20$ mm unaltered, and then extracting the apparent compressive modulus by converting the load/displacement ratio into corresponding stress/strain relations.

Figure 16. Homogeneous finite element models of specimens with (a) square and (b) circular cross sections.

The FE study provides two significant findings, visible in Figure 17. Just like in the experiments the apparent compressive modulus is virtually identical for the two specimen geometries. The experimental results however showed a tendency towards slightly higher modulus for the cylindrical specimens. Secondly, the compressive modulus extracted from the load-displacement response initially increases with increasing in-plane specimen size, but appears to level out asymptotically for larger in-plane sizes. This variation is more pronounced when the Poisson's ratios is increased from $\nu=0.3$ to $\nu=0.4$, as shown in Figure 17. The phenomenon appears to be a shift from plane stress to plane strain, which is also supported by the following analytical expressions.

For plane stress

$$\sigma_{zz} = E \epsilon_{zz} \quad (1)$$

while for plane strain

$$\sigma_{zz} = \frac{1-\nu}{(1+\nu)(1-2\nu)} E \epsilon_{zz} \quad (2)$$

resulting in an apparent modulus of 540 MPa and 856 MPa for $\nu=0.3$ and $\nu=0.4$, respectively, when the relative specimen thickness approaches zero. The numerical results in Figure 17 correlate qualitatively very well with the experimental results in Figure 15. Note that the result for "zero" cross section area in Figure 17 should be identical with the Young's modulus of the material in the FE model and thus be 400 MPa sharp for both Poisson's ratios.

Figure 17. Modulus results from the FE analysis with a homogenous material model

4.1.2 Stochastic foam model – Study of effects from boundary conditions

In order to further conclude on the observations from the real foam experiments, a stochastic 3D model of foam based on Voronoi spatial partitioning and subsequent minimization of surface energy in the foam cell walls [28,29] is also incorporated in this study. The model is built as a representative volume element (RVE), using principles of 3-torus space to make it fully periodic in 3D. It can thereby be used to derive reliable homogenized material properties for cellular materials. In the present study the periodic boundary conditions are however partly removed giving the model finite size in some or all of its principal directions. The model can then be used to study the effects of various parameters and test conditions by altering the boundary conditions, and to some extent also the load introduction. Four different model cases are presented in Figure 18, intended primarily to further explore effects of finite size but also the presence of cut cells on the specimen boundaries.

The model contains 100 cells with spatially periodic boundaries and a relative density of 0.1. (100 cells were shown to provide converged results in a previous study [29] but the relative low number of cells makes the model represent just in the order of 1-10 mm² of the real foam, if the periodic boundary conditions are removed.) The FE model is meshed with 8-noded shear-deformable shell elements and analyzed with ABAQUS [27] assuming a bulk material modulus $E_s=11800$ MPa. The bulk modulus is chosen to match the stiffness of the homogenized FE model in the previous study in order to simplify comparisons. The stochastic model is however not geometrically matched with a specific foam material since the tested foams differ in relative density and likely also in distribution of material between cell walls and edges. (A deeper discussion of this matter is beyond the scope of this paper but partly given in [29].) The purpose of introducing the stochastic model here is primarily to explore effects of finite size and presence of open cells at the specimen boundaries.

The load is in most cases applied by assigning an identical relative displacement between all opposing node-pairs on the loaded surfaces. The load case thus resembles a case of constant pressure, which is slightly "softer"

than a prescribed uniform displacement on all surface nodes since it does not constrain the loaded surfaces to remain plane. The way the load is introduced enables direct evaluation of the modulus from the model since there is virtually no difference between the strain in the interior of the model and at the load introductions.

Case 1. Periodic - Periodic

The first case is a reference case with periodic boundary conditions on all exterior surfaces of the model, making it represent an infinite continuum. The model is intended to provide the true compressive modulus for the foam, corresponding to the Young's modulus assigned to the homogenized FE models in the previous section.

Case 2. Periodic – Prevented transverse expansion

In the second case the load is applied similarly as in Case 1 but preventing out-of-plane displacement of the unloaded surfaces. Periodic in-plane deformation of the unloaded surfaces however still prevail making the case representing plane strain loading conditions, as discussed in the previous section.

Case 3. Periodic - Free

The third case represents the experimental test situation with a finite size specimen. The load is again applied similarly as in Case 1 but here the periodic boundary conditions are removed from the unloaded surfaces, making them totally unconstrained. Since the model only contains 100 cells, relatively many (about half) of them are in contact with the model boundaries. These cells are thereby cut open and when the periodic boundary conditions are removed any effects of finite size and free edges should show.

Case 4. Clamped - Free

In the fourth case the in-plane deformation of the loaded surfaces is constrained while the unloaded surfaces are totally free, similarly as case 2. Lateral expansion is thus permitted everywhere but on the loaded surfaces where a uniform prescribed displacement is applied. The case represents a test of a finite cubic specimen that is bonded or tied by friction to infinitely stiff load-introducing plates, resembling the bonded case in the experimental section, although the FE model is much smaller than the tested specimens.

Prescribed nodal displacements (pairwise between opposite nodes in Cases 1-3 and uniformly in Case 4) corresponding to a compressive strain of 1% is applied in one principal direction (x, y and z) at a time, for all mentioned cases. Stresses and strains are extracted and used to compute the compressive moduli. Figure 19 summarizes the compressive modulus results as averages from the three principal material directions for all FE test cases.

Figure 18. FE simulation cases using a stochastic inhomogeneous foam model

Table 7. Results from the stochastic amorphous FE model with varying boundary conditions

FE, inhomogeneous 3D foam model	Modulus [MPa]			
	E_x	E_y	E_z	$E_{average}$
1 Infinite size – periodic continuum	406	392	402	400
2 Infinite width – periodic-constrained, plane strain	566	553	563	561
3 Finite size – periodic-free, with cut cells on edges	362	350	350	354
4 Finite size – clamped-free (resembling bonded)	400	386	386	391

Figure 19 Modulus results from the FE analysis using a stochastic inhomogeneous foam model

The modulus from Case 1 comes out identical with the Young's modulus assumed for the homogenized FE models in the previous study. As mentioned above, that is not a coincidence but deliberately achieved by choosing a suitable bulk material modulus for the amorphous FE model. The result is representative for the "true" foam modulus under plane stress conditions.

The modulus coming out from Case 2 is representative for plane strain conditions. It is 40% higher than the (plane stress) modulus from Case 1, which indicates a Poisson's ratio of 0.3138 according to eq. (2). The only reason for giving the result with that many digits is that the Poisson's ratio derived from the average lateral expansion in Case 1 is 0.3137 and the two indicators are thus in perfect agreement. The result is also in very good agreement with those extracted from the DSP analysis of the R200H foam in the experimental investigation.

Results from the FE simulations are presented in Figure 20 where the prescribed displacement is applied in the x -direction for all four cases. The prescribed displacement is not easily seen in the figure but color (or gray-scale) is used to show the (normalized) transverse displacements in one direction (z) for the different cases. Presenting the global strain is infeasible for the models since only the strains in the cell walls can be easily extracted from the FE results. The homogenized strain of the whole foam sample is thus better visualized through the corresponding displacements. As seen the transverse displacement varies evenly in Case 1 (Figure 20-1) and is virtually zero in Case 2 (Figure 20-2).

Case 3 represents a finite size specimen with free transverse expansion. The modulus comes out 22% lower than for Case 1 and the reduction is due to the presence of the open (cut) cells at the unloaded surfaces of the model. A complementary parameter study was performed, presented in a following section.

Note that the differences in boundary conditions are hard to distinguish in the FE plots of the different cases but it is clear from Figure 20 that Case 3 shows both more uneven and relatively higher displacements than Case 1.

Finally Case 4 represents a situation where the loaded surfaces are constrained in-plane, resembling e.g. friction (no slip) or adhesion to the loading platens. The unloaded surfaces are totally free and the case should thus be

compared with Case 3. The added constraint on the loaded surfaces then increases the modulus with about 10%, which is again assumed to be quite extreme due to the low number of cells in the model (assuming that the edge constraint only influences the outermost cell layers). Only a small difference is also observed in the tests (see Table 5) but it should be noted that the bonded case differs from the rest by showing a higher stiffness from Ext.1 than from Ext.2. Although the difference is small and not statistically certain it might indicate a slight stiffening effect from the constraints on the loaded boundaries. It can be seen in Figure 20-4 that the deformation is much higher in the middle of the specimen than at the loaded surfaces (where it is zero) and the fact that in-plane displacement of the loaded surfaces is prevented increases the local compressive stiffness.

The modulus from Case 4 only differs marginally from the "true" modulus from Case 1 but that is believed to be merely coincidental. The reduction due to the cut cells at the un-loaded surfaces happens to be of similar magnitude as the increase due to the constraints on the loaded surfaces so the two opposite effects on the modulus virtually cancel out for the specific case at hand.

Figure 20. Comparison of the effect of boundary conditions (Cases 1-4) looking only at the normalized transverse expansion in the z -direction. The models are compressed in the x -direction

4.1.3 Stochastic foam model – Study of effects of finite size

Due to the relatively low stiffness of Case 3 above and the plausible coupling to the number of cells in the model a few more simulations were made. One model each was run containing 50, 100, 150, 200 and 250 cells,

with the same loading and boundary conditions as in the original Case 3. The results are presented in table 8 and confirm a weak but consistent increase of stiffness with the number of cells in the model.

Table 8. Results for Case 3 from stochastic amorphous FE models with varying number of cells

Number of cells	Modulus [MPa]			
	E_x	E_y	E_z	$E_{average}$
50	348	359	367	358
100	369	369	373	371
150	369	381	373	374
200	373	372	379	374
250	385	376	379	380

Assuming that there is a surface effect related to open cells at the model boundaries there is reason to believe that the stiffness decays outwards from the core of the model when approaching its free edges. It is then also reasonable to assume that the thickness of this more compliant “skin” is relatively independent of the number of cells, provided that the model contains a sufficiently large core of intact cells.

If a cubic RVE model of a certain volume V contains N cells the average (nominal) cell diameter is

$$d = \left(\frac{6V}{N\pi} \right)^{1/3} \quad (3)$$

and the RVE side length l then relates to this diameter as

$$l \sim dN^{1/3} \quad (4)$$

A very simple but practical assumption is that a zero stiffness skin of thickness αd can approximate the compliant surface layer. The RVE stiffness is then given by

$$E_N = \frac{(N^{1/3} - \alpha)^2}{N^{2/3}} E \quad (5)$$

where E is the true (average) modulus of the foam. Now performing a least square fit, using Eq. (5) and replacing E_N with the stiffness $E_{average}$ results from Case 3 presented in Tables 7 and 8, α comes out as approximately 0.25 and E as approximately 410 MPa. (Since there are modulus results from two models containing 100 cells – the original and the new – their mean value is used.) The α result indicates that the surface effect is confined in the very proximity of the model boundaries and just affects a layer that is considerably thinner than the nominal cell size. The result for E is surprisingly close to the true 400 MPa (< 3% off), considering that only one model each was used for the cases with 50, 150, 200 and 250 cells. For the case with 100 cells two models were used and as seen in Tables 7 and 8 the difference in modulus between the two supposedly similar models is almost 5%, coming from their stochastic nature.

The reduction of modulus in the Case 3 FE simulations is quite extreme due to the low number of cells in the models, which brings about half of them in contact with the model boundaries and thereby cut open. It should however be noted that the cases with periodic boundary conditions (Cases 1 and 2) do not suffer from this effect. The result also indicates that the effect of open cells in the experiments is of lower significance since the ratio between the cell and model size is orders of magnitude lower in the experiments than in the FE model (about 10^{-3} in the experiments compared to about 10^{-1} in the models).

5 Discussion and conclusions

The results from this study clearly indicates that the compressive strain should be measured only over the interior part of the tested specimens (here referred to as the *net strain*), i.e. the gauge length should not exceed the thickness of the foam material. That is to avoid errors due to local effects at the loaded boundaries, which primarily are due to uneven load introduction causing high local strains in the vicinity of the load introductions.

(Bonding the specimens to the load platens could thus provide more accurate results if the *gross strain* is used but that is both impractical and could have the opposite effect on the results due to stiffening from the adhesive and/or the constraints it imposes).

The conclusion that the net strain should be used is supported by the fact that the compressive moduli then come out very similar to the tensile moduli provided by the manufacturers. Total agreement should however generally not be expected since they are typically measured in different material directions and many foams are slightly anisotropic.

The results from FE simulations, using very realistic amorphous 3D foam models, show a certain effect from the cut surfaces containing open and thereby more compliant cells. The effect is however deemed to be insignificant for most practical cases since the FE simulation indicates that it acts at a length scale smaller than the cell size which is typically several orders of magnitude smaller than the width of the specimens used in compressive tests.

A specimen size effect is more prominent both in results from experiments and from homogenized FE models. If the specimen width to thickness ratio is too high there is a risk that the compressive modulus is overestimated since friction on the loaded surfaces may shift the loading condition from plane stress towards one of plane strain. The study indicates that the width to thickness ratio should preferably not exceed unity in order to avoid significant underestimation of the modulus. This result is in discord with the specifications in the ASTM D1621 test standard to date [18], which virtually recommends the opposite. The most recent ASTM C365/C365M test standard [19] gives no specification of the thickness but only on the in-plane dimensions of the specimens. It should be noted that a consequence of this finding is that several of the experimental results presented in the paper likely overestimate the foam moduli to a certain extent.

In the parametric study there is possibly a weak tendency for the cylindrical specimens showing slightly higher modulus values than the block specimens, but it is too small to be statistically certain. No such difference is found between the corresponding FE simulations, which is not a surprise since those FE models have homogeneous material properties. The surface layers of the real foam specimens however contain open cells, which should decrease the stiffness somewhat, and the fact that the cylindrical specimens have a slightly smaller circumference area for the same cross section area might explain their apparent higher modulus. The results from the more realistic inhomogeneous FE models however indicate that this effect should be insignificant for the specimen sizes in the tests and the seemingly consistent difference between the cross section shapes is therefore ruled out and rather deemed coincidental.

If the specimen size is very small, the measured compressive modulus could be underestimated due to the presence of cut (open) cells at the specimen boundaries. As a rule of thumb specimens should at least contain $>10^4$ cells to provide reliable results without compensation for edge effects. The effect is thus more prominent for small sample sizes of foams with relatively large cells and should not be a significant source of error if the smallest characteristic size of the specimen exceeds that of the cells with two orders of magnitude or more.

Some of the localized strains at material interfaces might be artifacts by the DSP software, related to insufficient resolution. Quantification of local strains is cumbersome but regardless of that there are clear indications of true strain concentrations at the specimen boundaries, which contribute to underestimation of compressive moduli if they are included in the strain measurements. Apart from the high strains at the load introductions the strain through the thickness varies very little.

As a final remark, the paper did not address the compressive strength of the tested foam materials since it seemed to come out consistently regardless of the method used in the experiments.

6 Funding

The present work has been performed with support from VINNOVA (Swedish Governmental Agency for Innovation Systems) under the NFFP6 project no. 2013-01132 (DAMTISS).

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