Compression Fatigue Testing Setups for Composites—A Review

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The positive combination of lightweight design and high fatigue resistance of fiber reinforced materials has led to their broad application in many different structural applications. During the design phase, it is often only considered that these materials are subjected to tensile loading conditions to make use of their excellent strength and fatigue resistance properties. However, in the current challenge to reduce weight of transportation vehicles, a broadening range of loading conditions for composites may arise, whereby it is not always possible to restrict loading to pure tensile conditions. In contrast to metals, compressive loading is a challenging load case for composites. Much research is undertaken to understand the compressive behavior of composites and to develop valid methods for their characterization. Especially for compressive fatigue testing (load ratio $R < 0$ and $R > 1$), the generally accepted methods are rare, and not much is reported in the literature on how characterization should be done. This review provides an overview of existing methods, i.e., setups for testing fiber reinforced polymer composites under compression and discusses their applicability to fatigue testing.

1. Introduction

Continuous fiber reinforced plastics show major advantages in tensile loading conditions. This is especially true for cyclic loading due to the good fatigue performance provided by glass and carbon fibers. However, it is widely accepted that compressive loading is a critical load case for most composites. For fiber reinforced plastics, this is mostly due to instabilities on different length scales—beginning at the smallest scale with microbuckling of single fibers to instabilities of fiber bundles, namely, fiber kinking, up to global buckling of the hole laminate. The sequence of events is hard to discern for quasi-static testing, and often, it remains unclear as to the cause of failure. This is even more the case for compressive fatigue testing. Different approaches can be found in the literature on how fatigue tests should be performed. A mandatory requirement for reliable design data is tested under conditions found in subsequently manufactured components. Therefore, it is generally sought to prevent the global buckling while allowing for all other damage mechanisms to take place. Two main testing strategies for axially loaded plates or strip-like specimens can be identified to achieve this goal. One common strategy is shortening the gauge length to a value where global buckling occurs after compressive failure. The second approach uses anti-buckling guides to prevent global buckling. These testing strategies are established methods for static compression testing and are sometimes also used for fatigue testing. However, the number of fixtures in both approaches is numerous, and only some of the fixtures are viable for fatigue testing. These generally accepted methods for compression testing are supplemented by different specimen geometries or loading conditions. A generalized overview is given in Figure 1.

2. Failure Modes

2.1. Compressive Failure Modes in Fiber Reinforced Composites

The properties of fiber reinforced plastics depend mainly on the type of reinforcement chosen as well as the stacking sequence of layers within a laminate. For compressive loads, the matrix

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material is of much greater importance for the facilitation of good fiber properties compared with tensile loading. As the high strength of typical fiber materials can only be achieved by small diameters, the flexural stiffness of fibers is typically low and, therefore, also has the ability to bear compressive loads due to an early onset of deformations due to instabilities.\cite{1} The matrix material has to prevent or delay this off-axis movement of the fibers at higher loads or increased number of cycles in the case of fatigue loading. This type of compressive failure is known in the literature as micro-buckling. Budiansky and Fleck\cite{1} provided an extensive review on available models describing this type of damage. On the mesoscopic scale, the same can be observed for single plies, which also show a small flexural stiffness on their own. Higher compressive loads can only be realized by the matrix material and bonding at the fiber–matrix interface. Damage on this scale is assumed to occur due to delamination and longitudinal splitting.\cite{2} Another mesoscopic failure modes are kink bands. The formation of kink bands involves a bundle of fibers, which are displaced relative to the undamaged state. However, it remains unclear if the kink bands are the result of other damage mechanisms, fiber misalignment due to manufacturing, or a damage mode of its own.\cite{2}

2.2. Compressive Damage in Fatigue

In contrast to failure modes observed under static compression testing, not much is reported on damage modes observed under cyclic compression loading (e.g., $R = 10$). Some general conclusions can, nevertheless, be drawn. For layups with pronounced edge effect, it is frequently reported that localized delaminations form at the free edges of plate-like specimens. During cyclic loading, these delaminations grow, leading to a loss of structural stiffness, and final stability failure of the specimen occurs.\cite{3}

This would make layups containing angle plies in the range of $\pm 10^\circ$–$15^\circ$ especially prone to delaminations starting from free edges.\cite{4} An experimental study of different carbon/epoxy layups under compressive loading showed that for layups containing fibers along the loading direction, no stiffness degradation is present. This was not the case for laminates with [90] or $[\pm 45]$ reinforcement where a stiffness degradation was present, which was attributed to a deteriorating fiber–matrix interface. In terms of fatigue ratio, the S–N curve of multidirectional laminates $([\pm 45]/0/90)$ shows a reduced slope compared with unidirectional laminates. The difference is explained by the stabilizing effect of off-axis layers. In contrast to other investigations, the influence of delamination growth is not mentioned.\cite{5}

3. Axial Loading Methods

3.1. Short Gauge Length Testing

A short gauge length is generally accepted for static compression testing. From extensive literature reviews on quasi-static compression testing, it becomes clear that many researchers focused on different testing methods for specimens with short gauge length.\cite{6} These methods differ typically in the way axial compressive loads are applied and can, therefore, be categorized as follows: 1) load introduction by shear loading; 2) load introduction by end loading; and 3) combined loading concepts.

The focus on load transfer for small gauge lengths is driven by the necessity to achieve a uniform compressive stress distribution in the gauge length and, at the same time, prevent global buckling of the specimen. To fulfill both requirements, two limits for the free gauge length exist. The minimum gauge length can be estimated using a modified version of the St. Vernants principle for anisotropic composites. This principle describes the necessary distance for a stress concentration to reach the undisturbed stress state. The results obtained for unidirectional laminates show that the decay length is a function of specimen thickness, longitudinal elastic modulus, and shearing modulus.\cite{7} The upper bound for an unsupported gauge length is restricted by the buckling load of the specimen. A short gauge length allows only for slight cross-sectional changes by lateral or thickness tapering, as, otherwise, the notch effect prevails. An overview of typical fixture designs is given in Figure 2. The compressive fixtures represented are reported with their mostly referenced designation.

3.1.1. Shear Loading

One widespread compression loading fixture is the Illinois Institute of Technology Research Institute (IITRI) fixture, which
gave way to many modified versions of the basic principle. Another similar shear-loaded fixture is the Celanese-type fixture. Instead of wedge-shaped grips, conical grips are used. Both aforementioned fixtures are solely able to transfer compressive loads, due to the self-adjusting gripping stress. The ratio of axial force to gripping stress is defined by the wedge or cone angle. For fatigue testing, these concepts would prohibit any loading cycle, which incorporates tensile loading. Friction and changes in friction can further hinder the unmodified use of IITRI and Celanese for fatigue testing, as this problem is already frequently reported for quasi-static testing with the Celanese fixture. Differences in friction between the conical grip parts can lead to bending and premature buckling of the specimen in quasi-static testing.[8] For small deviations in specimen thickness or alignment of the conical grips, the contact surface becomes a line rather than full surface contact, which could easily lead to fretting corrosion within the grips and changes in specimen loading under cyclic loading. This along with a second load path introduced by the outer pipe-like alignment sleeve impedes the use of this fixture for fatigue testing.[9] Some modified versions of the initial design use intermediate designs between a cone and a wedge to enable variations in specimen thickness or use a wedge in corporation with the alignment sleeve of the Celanese fixture.[10] Despite some intermediate wedge–cone designs, as shown in Figure 3, the problem remains that small imperfections lead to higher pressure in the contact zone between gripping and casing, and wear could be a problem in cyclic loading. This might also be the reason why no literature exists on the usage of this fixture for cyclic compression loading could be found. The problem of friction and clamping pressure is also reported for the IITRI-type fixtures.[7]

Also, problematic could be the self-adjusting gripping stress as a function of wedge or cone angle. The upper bound of gripping angle is mainly driven by the need to prevent the specimen in

Figure 2. Typical loading concepts used for compression testing.
Whether a combined or pure shear loading was used, reversed fatigue loading can be found in Rotem and in the transition region from the grips to tabs and gauge length. This would then lead to higher stress concentrations by gripping stress would be observed for the highest loaded carbon-fiber reinforced epoxy specimens. This is not reported. However, equal stress states under tension and compression would suggest pure shear loading. The unidirectional and cross-ply laminates failed by the formation of delaminated areas followed by global specimen failure.

A study of carbon reinforced epoxy with different layups ([0], [0/90], and [±45]) using a slenderness ratio of 7.5 under reversed fatigue loading can be found in Rotem and Nelson. Whether a combined or pure shear loading was used is not reported. However, equal stress states under tension and compression would suggest pure shear loading. The unidirectional and cross-ply laminates failed by the formation of delaminated areas followed by global specimen failure.

A third concept for shear loading of the specimen was developed by the National Bureau of Standards and, hence, is known in the literature as National Bureau of Standards (NBS) fixture. The load transfer is achieved by friction onto a cylindrical clamping surface, which is bonded to the specimen with either round or rectangular cross section and could be described as cylindrical tabs. Initially, the design was intended for static compression testing but was also extended to compression-compression testing of boron-fiber reinforced epoxy and aluminum under cryogenic conditions. It is reported that the specimens broke by shearing failure under 45° to the specimen axis; however, no failure location is described.

Shear loading is commonly used for fatigue testing, likewise, for tensile or compressive loading. Most hydraulic grips use the movement of a hydraulic piston to clamp wedge grips. Some concepts, which are based on the initial IITRI design, also use hydraulic grips in combination with the linear bearing for better alignment. Other researchers also reported good results by the use of hydraulic grips for shear-loaded specimens in compression-compression (R = 10) testing of carbon epoxy laminates.

Hydraulic clamps without additional alignment were also successfully used for fully reversed fatigue testing of carbon fabric reinforced polyimide. In terms of alignment errors, it is important for compressive loading to consider the relatively low lateral stiffness of many hydraulic testing rigs.

3.1.2. End Loading

End loading of the specimens is the second line of compressive fixtures developed. Reasons for their use are that the point of load introduction is distant to the gauge length, and the designs are mainly simple to manufacture. However, crushing and splitting of the specimen end are likely. The two most common designs, which can be found in the literature, are the Boeing-modified American Society for Testing and Materials (ASTM) D 695 fixture and the Wyoming end-loaded, side supported (ELSS) method.

The Boeing-modified ASTM D 695 fixture uses different specimens for compressive strength and modulus measurements. For measuring the compression modulus, a specimen without tabs is used, whereas a specimen with end tabs is used for the determination of compressive strength. For composites, a modified version of this end-loaded fixture is only used, because the design originates from a fixture for unreinforced and dog bone-shaped specimens rather than straight-sided specimens. Both concepts make use of an out-of-plane support either directly by metal plates (ELSS) or by the use of tabs in combination with metal supports. In both fixtures, slightly tightened supporting plates at the specimen ends prevent splitting and crushing. For fatigue testing, it can be expected that the probability of splitting and crushing might be enhanced further. Changes in the specimen geometry could mitigate the problem. Depending on the type of reinforcement, it could be feasible to use a tapered specimen in terms of width. This method was successfully used for testing of carbon-fiber fabric reinforced polyimide under fully reversed loading (R = −1). In addition, the residual compression strength was determined with the same specimen geometry and a slenderness ratio of 7.1, which is the ratio of unsupported length to specimen thickness. This example shows that a tapered specimen is for certain types of reinforcement feasible even though the load was introduced by pure shear loading. The second method to prevent splitting is already used for strength measurements with the Boeing-modified ASTM D 695 fixture. However, using tabbed specimens, this method essentially becomes also a combined loading method in terms of tested laminate, because the load is...
partially transferred by the bonded tabs through shear stresses away from the specimen end. By increasing the thickness of the tabs, more shear loading can be applied, but then again the disadvantages of stress concentrations and highly constrained transition regions become relevant. In addition, the adhesive used to bond the tabs is more likely to fail.\(^{[21]}\)

Another method to accomplish end loading without splitting can be achieved by bonding metal plates to the loaded edge or even to immerse the ends in grooves filled with glue.\(^{[23–25]}\) This specimen is also known as the Royal Aircraft Establishment (RAE) specimen. A groove is manufactured in metal plates to accommodate the ends of a thickness tapered specimen. The RAE specimen uses a thickness tapered geometry with a relatively long unsupported length, which makes the specimen prone to global buckling. The role of global buckling for this method has been investigated by filling the gap between the grooved plates with unreinforced epoxy to support the specimen. The comparison of epoxy stabilized and unsupported specimens leads to the same compressive strength.\(^{[25]}\) The bonded ends are similar to the NBS specimen and could, therefore, also be viable for a fatigue test. No reports on applications of the RAE specimen for fatigue testing could be found. However, the concept of thickness tapering can also be found for the IITRI type fixture and shear loading. Adams and Finley reported the tapering radius to be a measure to shift the failure location away from the grips.\(^{[20]}\) Results of finite-element analyses promote a large tapering radius to reduce the through thickness shearing stresses.

In contrast to the RAE specimen and the Boeing-modified ASTM D 695 fixture, reports on fatigue testing with a design similar to ELSS of carbon- and glass-fiber reinforced epoxy can be found.\(^{[26]}\) In the original design, alignment of the plates is achieved by linear bearings. The David Taylor Research Center (DTRC)-modified concept also uses end loading in combination with supporting plates for thin specimens but allows for adjustment of the lower plate.\(^{[27]}\) By allowing one plate to adjust to misalignments and geometry variations, the Euler buckling factor \((k\) in Equation (1)) is 0.7 instead of 0.5, and the buckling length is artificially prolonged. Therefore, the specimen’s slenderness ratio is of even more concern, and the method is limited to thick laminates.

### 3.1.3. Combined Loading

The combination of shear and end loading attempts to overcome the problem of shearing failure and end splitting by relieving the highly stressed regions. A numerical study of combined and pure end and shear loading methods could show that for the combined loading method, two relevant stress peaks can be reduced, namely, the shear stress peak at the specimen ends for tabbed and end-loaded specimens and the stress peak at the tab tip.\(^{[28]}\) Another benefit of this loading method is that the decay length to achieve a uniform stress distribution in the short gauge length can be reduced by combined shear and end loading. However, one major issue especially for cyclic tests remains for many setups in the overdetermined clamping configuration. Typically, the specimen’s compliance is used as measure to define the magnitude of end loading. Three concepts for defining the ratio of end to shear loading are shown in Figure 4. Concept a) uses an initial clearance to define a minimum force at which the end loading becomes active. The timing of end loading contact is crucial and must be simultaneous for both ends of the specimen. To further protect the ends from splitting, steel plates are applied.\(^{[24]}\) Some problems may arise if this concept is used for compressive fatigue testing, as the loading cycle may span the point of pure shear loading and combined loading. Other concepts use initial contact between the specimen end and the loading plate or spacers. This combined loading method is also standardized for static compression tests in ASTM D 6641 and was used for compression–compression testing of thick laminates.\(^{[29,30]}\) The comparison of static compression strength for different gripping pressures or end to shear loading ratios shows that the correct gripping pressure is mandatory for correct measurements.\(^{[30]}\) For thicker specimens, this also mandates a longer clamping length to keep the gripping pressure optimal for increasing test loads. Regarding the thickness of the specimens, the authors could show the stress gradient not only by numerical modeling, but also by strain gages bonded at the tabbed surface and the specimen’s lateral sides. As Lahuerta et al. pointed out, this effect makes the outer layers more likely to fail.\(^{[10]}\) This along with the stress concentration at the transition from tabbed to untabbed area corresponds well to the fact that only a small number of
specimens failed within the gauge length. This effect was more pronounced for fatigue loading. For concept b) in Figure 4, the ratio of shear loading and end loading is mainly dependent on the gripping force and the interlaminar shear stiffness of the specimen or, in case of bonded tabs, the combined shear compliance. This method has been used for the investigation of layer waviness in carbon reinforced epoxy under compression-compression loading ($R = 10$). For small waviness, most specimens failed inside the gripping area.

A third combined loading fixture c) overcomes the problem of an undefined ratio of end to shear loading using a system of levers, which distributes the load according to length ratios on the specimen end and the wedge grips. Bech et al. used the mechanical combined loading (MCL) fixture for quasi-static loading as well as for compression–compression fatigue loading. Although the first results showed some problems of specimen bending, it seems promising to define the ratio of combined loading in terms of geometric parameters rather than mixed parameters of compliance and geometry as in a) and b).

### 3.1.4. Concluding Remarks on Specimens with Short Unsupported Measuring Length

As much work was done on the correct load introduction into the gauge length, the use of combined loading or pure shear loading seems to be the most promising ways for introducing the testing loads. As many concepts for compression testing have their origins in quasi-static testing, many fixtures incorporate mechanically applied gripping pressure. These concepts have the benefit of an independent use without hydraulic supply but come with disadvantages such as a possible decrease of screwing torque and differently constrained specimen ends by self-adjusting wedge designs. Both effects can alter the specimen's end constraint and, therefore, also the uniformity of compressive stress and stress concentrations. In any case, as scattering in compression–compression fatigue is usually higher compared with tensile loading, the most reproducible loading method should be chosen to avoid additional deviations. The upper bound of the gauge length is determined by the Eulerian buckling load. As all methods are based on the assumption that bifurcation happens long after compressive failure, a good alignment and parallel specimen edges are key to the successful application of all methods.

### 3.2. Testing with Long Gauge Length

Many of the aforementioned problems such as load introduction into the specimens remain also for a longer gauge length. However, the problem of non-uniform compressive stress and stress concentrations can be overcome by a longer gauge length using width tapered or thickness tapered specimens or just by increasing the gauge length itself. The resulting high slenderness ratio makes global buckling possible. To prevent buckling, an anti-buckling guide is typically used. In contrast to many quasi-static fixtures, this concept finds its use more often in compressive fatigue testing and only seldom in the context of quasi-static testing. Of major concern is usually friction between the supporting plates (anti-buckling guide) and the specimen, which could lead to a second load path and, thereby, artificially increased compressive strength, enhanced hysteresis opening, and generally a stiffer specimen. Depending on the surface quality, geometric links can be of concern as source for the second load path as well. If friction or geometric links occur, the specimen's surface can also be damaged in repeated loading. Different methods for reduced friction and lateral support can be divided by the type of contact into three main categories; see Figure 5. The first category makes use of surface contact, which theoretically brings the specimen’s surface in full contact with the support plate. The second group makes use of a number of line contacts either in loading direction or transversely. The last category makes use of several point contacts.

#### 3.2.1. Surface Contact Supports

Friction is especially of concern for surface contact supports. Šeruga et al.[31] evaluated friction between supports and cyclically loaded sheet metal specimens. As a measure to limit friction, the researchers used a polytetrafluoroethylene (PTFE) layer and

![Figure 5. Anti-buckling supports divided by the type of contact.](www.aem-journal.com)
chose only slight pressure on the supporting plates. The specimen’s deformation facilitates a relative displacement between clamps and anti-buckling device, which is used in the experimental setup to measure the frictional forces. These measurements show that friction is also of concern even if the initial pressure of anti-buckling plates is low. This is due to buckling of the specimen and, hence, contact to the supporting plates. This was shown by friction force measurements, which show that contact only happens above the critical buckling load.\(^{[31]}\) The comparison of steel and aluminum sheets shows that friction is mainly observable for the cyclic stress–strain curve of the less stiff material, i.e., aluminum. In the context of composite materials, greater effects are to be expected for laminates with more off-axis reinforcement and, thus, lower stiffness. Shape, size, and location of the unsupported area between the moving grips and the anti-buckling guides distinguish between partial and full surface contact, due to typically larger unsupported areas for a chevron-shaped separation. Ryder and Black\(^{[32]}\) used a full surface supported composite specimen. The presented method uses a gauge length of \(\approx 133\) mm, whereupon 129.5 mm are fully supported. A PTFE foil was used to reduce friction between specimen and supporting plates. The specimens were essentially tensile specimens similar to DIN EN ISO 572-3 with one tab cutoff to allow for end loading.\(^{[33]}\) Compared with results with the Boeing-modified ASTM D 694 fixture, end splitting is not the main failure mode of the quasi-isotropic carbon epoxy laminates.\(^{[21,32]}\) One possible reason, besides the tested material, is the full surface support near the loaded edge, whereas only a number of line contacts are present in the Boeing-modified fixture. However, this design is only reported for static compression testing. Without tabs to reduce the compressive stress at the specimen ends, it seems likely that under repeated loading, micro-buckle initiation at the specimen ends happens and damage begins to grow until splitting or crushing makes continued loading impossible due to blocking in-between the supporting plates. The likely initiation of micro-buckles at the loaded ends is shown by numerical investigations.\(^{[34]}\) Jeon et al.\(^{[35]}\) showed the feasibility of a fully supported specimen under fully reversed fatigue loading for glass-fiber reinforced epoxy.

Full surface contact supports often include a window for strain measurements or to provide better heat transfer (refer to Figure 6). Depending on window size, the anti-buckling support is similar to pure edge support or full surface support. Using a window or just edge support, planar buckling modes become possible. The influence of window size on the achievable fatigue life has been shown for notched graphite epoxy laminates.\(^{[36]}\) The results show a correlation between window size and fatigue life. This effect is explained by local instabilities due to delamination growth, which lead to premature specimen failure within the unsupported specimen section at window. From these findings, it seems possible that for some cases, their might be a correlation between supported surface or window size and compressive fatigue failure. For a better understanding, which window size is feasible for a given material, the theory for buckling of thin plates can be used. For an isotropic material, the lowest buckling load is obtained for quadratic plates under edge loading, which would correspond to a quadratic window.\(^{[37]}\) Nevertheless, the critical load for a plate with window is at least four times the value, obtained for buckling of a single strip of material.

Matondang and Schütz\(^{[38]}\) investigated the effect that the lateral position of surface support plates with respect to the specimen’s edges has. The tests were done in fully reversed loading of carbon-fiber reinforced epoxy laminates with different lay-ups. The results show that for some lay-ups, there is an influence of anti-buckling support design and fatigue life as well as stiffness degradation. One of the investigated anti-buckling guides supports the specimen’s edges, whereas the other does not. The results show that supported edges lead to a higher fatigue strength and stiffer stress–strain response. It is concluded that by supporting the free edges, an opening of delaminations is restricted.\(^{[39]}\) These findings are in accordance with Komorowski et al.,\(^{[3]}\) who also found that for compression–compression loading, delaminations develop localized at the free edges of the specimen and grow from there until final failure occurs. Similarly, the earlier findings for holed specimen point toward a correlation between out-of-plane support and delamination growth.\(^{[36]}\) Similarly, the out-of-plane constraint was found to increase the in-plane transverse strain of a specimen, as this was the unconstrained direction.\(^{[25]}\)

Another anti-buckling guide using surface contact for fatigue testing is presented by Tost et al.\(^{[39]}\) Instead of using plate-like specimens, the researchers use a thickness and width tailored specimen to reduce stress concentrations. The specimen design is optimized for fatigue testing of unidirectional glass-fiber reinforced epoxy materials. The use of an anti-buckling guide for

![Figure 6. Additional parameters for anti-buckling guide design.](image-url)
thickness tapered specimens is achieved by inserting a compliant layer of polyurethane (PU) between the supporting plates and the specimen surface. The low stiffness of the compliant PU layer allows specimen movement. To verify that no second load path exists, the hysteresis under reversed loading is analyzed. Furthermore, the method is verified by fully reversed fatigue testing of glass-fiber reinforced epoxy specimens.

All aforementioned full surface supports provided a clearance between the grips at the top, bottom, or on both sides of the supporting plates to allow for grip movement. The remaining unsupported specimen length can be a problem, as buckling again becomes possible if a compliant specimen or large gauge length is used. An alternative is the use of a chevron-shaped or V-shaped separation. This type of separation has the benefit that for each unsupported area, neighboring segments provide lateral support, because the first-order buckling would lead to bending with shifted positions of maximum displacement. The so-called Atmurl fixture was used for fatigue testing of carbon-fiber reinforced epoxy in compression–compression loading incorporating a chevron or V-shaped separation. Another fixture, which uses a chevron-shaped separation and a window, is the Suppliers of Advanced Composite Materials Association (SACMA) fixture. Johnson et al. used a modified version of the SACMA fixture with lighter and thinner supporting plates. Under quasi-static loading, they found the modified fixture to be satisfactory. Specific for both fixtures is that the ends are clamped together with the specimen inside hydraulic grips.

3.2.2. Line Contact Supports

As already discussed, the Boeing-modified ASTM D 695 is one method, which uses line contact to prevent a second load path. The fixture uses V-shaped grooves, which allow for limited contact between supports and specimen surface. A line support along the specimens longitudinal axis might be a problem, as restricted out-of-plane movement could promote in-plane transverse strain in the laminate and might cyclically lead to longitudinal splitting. This failure mode might become more likely, as with increasing gauge length, the transversely reinforcing tabs are further away.

Line contact for fatigue testing can also be achieved using honeycombs as intermediate layer between the supporting plates. The general concept is first mentioned for static compression testing. Then, the measure has also been evaluated for glass-fiber reinforced polyamide 6 under compression–compression (R = 10) loading and tension–compression (R = −0.74) loading. In both cases, width tapered specimens were used without tabs. The benefit of honeycombs as an intermediate layer is a low in-plane stiffness, whereby a second load path can be prevented. Second, crushing of the honeycombs in the thickness direction induced by local delamination or damaging of the specimen allows deformation upon a specific critical supporting load, which enables kink band formation and delaminations to grow.

Another line support is achieved by applying rollers. The rollers shorten the free length, and the buckling mode can artificially be shifted to higher orders, which is done for fatigue testing of spot welded metal sheets. With a greater number of rollers, the buckling mode would shift to higher orders. The main benefit of using rollers instead of fixed surface or line contacts is the change from coulomb friction to rolling friction.

3.2.3. Point Contact Support

Deluy et al. used a similar concept for fatigue testing of artificially flawed carbon/epoxy laminates under tension–compression loading. The specimens (width = 76.2 mm) were manufactured with a square of PTFE sheet (12.7 × 12.7 mm) between the middle layers to artificially mimic a flaw. The specimens were loaded with a partially compressive load of R = −0.1. The support plates incorporate ball bearings to avoid friction. Instead of total failure, the onset of delamination is used as a criterion for failure. It is not reported, if any damage was induced by the pointwise rolling contact between specimen surface and ball bearings. Although a good support seems possible, under higher compressive loads, it is likely that the surface gets damaged.

3.2.4. Concluding Remarks on Long and Supported Gauge Length

Ball bearings as well as roller supports provide a promising way to reduce friction. However, in the context of compression–compression testing of composites to determine a fatigue strength, not much literature can be found using this method. For laminates with pressure sensitive surfaces, supporting rollers might be the better choice to reduce pressure peaks. Another potential problem when using rolling contact is the surface quality as well as a constant thickness, as both could lead to highly stressed regions.

Despite the form of contact between specimen surface and support, there are many aspects, which can influence the results. The following list gives an overview of possible parameters to be aware of: 1) global supporting stiffness in x-direction ε_{global} or out-of-plane constraint; 2) initial contact pressure (torque of screws); 3) local supporting stiffness (PTFE sheet, honeycomb, blank metal); 4) degrees of freedom of the supporting plates (e.g., rotation around x-direction, movement in y-direction); 5) location of unsupported length; and 6) shape of unsuppressed area.

3.3. Tab Material

As tabs are of great importance for reliable fatigue testing results for a short unsupported and for long supported gauge length, a short summary of tabs in the context of compression testing is given here. Tab materials and adhesives are typically the same as those also used for tensile fatigue testing. However, some aspects have more consequences especially for a short measuring length. For example, tab debonding can influence significantly the stress distribution in specimens with short gauge length. This is especially true for layups with large Poisson’s ratio. The comparison of tensile specimens with different layups showed that for ±45 laminates, tabbing leads to undesirable differences in the strain distribution, whereas for cross-ply and unidirectional layups, the influence is less significant. A non-uniform stress distribution is thought to be the reason for a decrease in static compression strength with decreasing gauge length of unidirectional glass-fiber and carbon-fiber reinforced material, even though for this type of material, the smallest effect must be
expected.\cite{21} Effects such as stress concentrations and failure near the tabs present in static loading usually get more pronounced for fatigue testing and make the evaluation of acceptable results even harder to discern. Another comparison of different tab materials under shear, end, and combined compression loading also show that by more compliant tabs, the stress concentrations can be reduced.\cite{28} Low stiffness tabs might reduce those problems, but for short gauge lengths, the inherent problem arises that the grips might come into contact.\cite{21} This might be even more pronounced for cyclic-loaded specimens, as creep and compression set are active. Research on different tab configurations in fatigue testing of a straight-sided AS4-3501-6 carbon epoxy laminate with short gauge length under static and fatigue (R = 10) loading shows that steel tabs even with chamfer lead to higher stress concentrations at the end of the tab.\cite{18} In addition to steel and glass-fiber tabs, an artificial debond at the edge of the tabs was investigated, as shown in Figure 7. Through this approach, the researchers were able to shift stress concentrations further inside the tabbed region.

3.4. Material Degradation and Buckling

A significant amount of research has gone into defining a viable gauge length for compression testing of composites under static loading.\cite{7} In fatigue testing of composites with loading cycles containing compressive and tensile loads, the problem of deteriorating material properties makes it nearly impossible to estimate the buckling behavior under fatigue loading, especially, as not much is reported on the stiffness degradation under such loading conditions. This is even more true as two elastic constants are necessary for the calculation of highly anisotropic material, namely, the elastic modulus along the loading direction and the out-of-plane shearing modulus. However, to get an estimate on the sensitivity of a reverse-loaded material, similarities between flexural fatigue and the relevant material properties can be used. Under the assumption that the flexural modulus accounts for the longitudinal stiffness and the shearing modulus simultaneously, the degradation should also correspond to the relevant material stiffness in Euler’s buckling formulations. With increasing crack density the Bernoulli assumption becomes more and more unrealistic, as the shear modulus decreases drastically.\cite{47} Hence, tension–compression loading would be especially affected.

By results obtained for the degradation of the flexural modulus in a three-point bending test of different layups of APC-2 (CF-PEEK), it becomes clear that degradation could be of relevance.\cite{48} As the flexural modulus is calculated from the displacement of the loading fin, it is a mixed material response of elastic and shearing modulus. Therefore, the increasing sensitivity to buckling can be estimated using this mixed elastic modulus in the form of flexural modulus in the Eulerian buckling formula (Equation (1) and (2)). The influence of different end constraints is included by k, e.g., k = 0.5, for fixed ends. The ratio of elastic modulus E to shear modulus G accounts for shear deformation by the original formulation of Timoshenko and Gere.\cite{37} The flexural modulus $E_{\text{flex}}$ could, hence, be an approximation for the diminishing factor (Equation (4)) for shear deformation.

$$F_{\text{cr, Euler}} = \frac{\pi^2 EI}{k^2 L^2}$$

(1)

$$\sigma_{\text{cr, Euler}} = \frac{\pi^2 Et^2}{k^2 L^2}$$

(2)

$$\sigma_t = \frac{\pi^2 Et^2}{L^2} \cdot \frac{1}{1 + \frac{1.2 \sigma_t \text{tab, unid}}{\sigma_t \text{tab, unid}}} \approx \frac{\pi^2 E_{\text{flex}} t^2}{k^2 L^2}$$

(3)

$$E_{\text{flex}} \approx \frac{E}{1 + 1.2 \frac{t^2}{12Gt^2L^2}}$$

(4)

As an estimate for the initial elastic modulus, the results from Carlile et al.\cite{49} are used. To account for stiffness degradation over lifetime, the initial elastic modulus is deteriorated analogous to the normalized flexural modulus reported by Buggy and Dillon.\cite{48} Using this estimation, it becomes clear that only for materials with rapid degradation of the elastic properties and high slenderness ratio (gauge length L divided by thickness t), buckling can be a problem in fatigue testing. In case of the analyzed layups only for the angle-ply material and a large slenderness ratio, a crossing point for buckling load and fatigue failure load is observable up to $10^7$ cycles; see Figure 8 and 9. This estimate does not account for two effects. First, the degradation will not be distributed uniformly along the specimen, as the bending moment is a function of distance to the supports, and second, the failure stresses in bending might be higher compared with axial compressive loading, as shown by the result of Carlile et al.\cite{49} Nevertheless, both effects change the curves the same way, which is lowering the expected stress for buckling and for fatigue failure. From these observations, it should be possible to use the material properties of undamaged material also for specimen design in fatigue loading and account for material degradation by applying a larger safety factor against buckling.

4. Bending Test

4.1. Bending Tests Using Sandwich Panels

The bending test is a standardized method used to evaluate the compressive strength of laminates. To perform such a test, a sandwich plate, e.g., a sandwich specimen, is used. ASTM D 5467 recommends suitable sandwich cores as well as the necessary thickness for the core and the two face sheets. To ensure a...
compressive failure of the specimen, the compressively loaded face sheet has a lower thickness. The static strength values are then calculated from elastic moduli and position of the neutral axis along with the applied load. It is important to note that even for the static loading case, a lot must be known about the elastic properties of the face sheets. An extension of this method to fatigue testing is not reported in the literature yet. Several reasons could hinder such an effort. First and foremost, it is very hard to design a specimen in a way that specific fatigue failure modes, e.g., compressive failure of the face sheet, can be expected. Nevertheless, reports can be found for specifically designed sandwich specimens for different failure modes.[50] However, this was only possible, because the components fatigue properties were known beforehand. As this would be not the case for compressive fatigue testing, an informed design is hard to achieve. Even if generalized failure maps could be drawn for typical laminate and core properties or from quasi-static tests, one has to keep in mind that a failure mode map would be a function of endured cycles. It changes due to different slopes of the S–N curves along with deterioration of the material properties as shown by Harte[51] for aluminum faced sandwich specimens. Furthermore, material deterioration makes it hard to discern the stress in the compressively loaded skin; therefore, only strain controlled fatigue testing could be performed. Nevertheless, general guidelines for specimen design with respect to compressive failure of the face sheet can be derived from literature on sandwich panels under flexural fatigue and static specimen design.[52] Some of the aspects which not only promoting compression failure but also indentation are: 1) smaller thickness for compressively loaded face sheet; 2) small ratio of core thickness to face sheet thickness; 3) sandwich core with high fatigue strength for compressive as well as for shear stresses; 4) large overlap of the specimen over the outer rollers can help to decrease the probability of core shear failure as far as yielding of the core can be prevented; 5) inner support distance has to be small relative to total support length; and 6) load introduction with large rollers or stress distributing layers to avoid indentation.

4.2. Bending Test Using Laminates

Instead of manufacturing a sandwich panel for testing of the face sheet under compression, some investigations make use of laminate bending to determine the compressive properties. Initially, longitudinal bending was used to study the size effect, because for different specimen thicknesses, the load introduction effects are not present. A similar stress distribution can then be achieved over the specimen’s cross section, which eventually leads to the observation of the influence between stress gradient and achievable compression strength.[53] As load introduction is one of the main problems, especially for compressive fatigue testing, the flexural method offers an alternative way of loading. As with many other methods, it was first used to determine the quasi-static compressive strength of unidirectional carbon/epoxy (T6T/F593) in a three-point bending test.[54] The compressive strength is calculated from the maximum applied load and geometry parameters. Seemingly, the method was also used in fatigue testing of carbon fiber reinforced polymer with \( R = 20 \).[55] However, no information is given on the type of failure observed or any details on the fatigue tests. A basic requirement for the applicability of this type of compressive fatigue test is that compression failure will occur before tensile failure; hence, the compressive strength transverse to the fibers of a unidirectional laminate cannot be measured by this method. Similar to the four-point bending test, the choice of specimen thickness and support roller distance influences the measured strength heavily. To avoid interlaminar shear failure, the support roller distance has to be large enough. In addition, the roller diameter correlates.
with the correct support length, as the contact area of load introduction can be influenced. Another way of choosing the right support distance is to evaluate the elastic modulus by a three-point bending test for different support distances. In this way, the elastic modulus shows an asymptotic behavior. Consequently, the minimum support distance can be chosen in terms of an acceptable difference to the asymptote, e.g., shear stress influence.

As experimental and numerical investigations pointed out, flexural compression testing has the inherent feature of a thickness-dependent strength value. By comparing the formation of micro-buckling in flexural testing and axial compression, an explanation for the higher compressive strength in flexural loading could be found. The formulated bending models for kink band formation in carbon-fiber reinforced plastic show that for a smaller specimen thickness, higher compressive stresses in the outer layers could be achieved, as a result of better support by neighboring layers. The performing researchers recommended a ratio of specimen thickness to fiber diameter greater than 1000. However, for different fiber-matrix combinations, this value can possibly change.

4.3. Concluding Remarks on Compressive Bending Tests

For stress-controlled fatigue tests, the material degradation can influence the measured fatigue strength, due to movement of the neutral axis. The latter would be the case if sections compressively loaded deteriorate differently in comparison with tensile loaded. Considering the interlaminar shear stresses, the necessary support distance could be even more important, because the failure mode might change over lifetime. This is true for bending of laminates as well as sandwich panels. Size effects and ply thickness can also be seen as major effects, which have only been partially investigated for static loading cases, and nearly no literature on flexural fatigue testing to investigate the compressive strength can be found.

5. Tubular Specimens

5.1. Outside Pressurized Rings and Tubes

One potential method to apply compressive stresses is to use hoop stresses in a ring or a tube. To achieve compression, outside pressure needs to be applied. One reported concept uses the Poisson effect of some compliant material, e.g., high density polyethylene (HDPE) or rubber to transform an axial deformation into radially acting pressure on the composite ring. This concept has the benefit of achieving a uniform compressive stress distribution in all cross sections. For thin rings, the stress gradient is very small. However, with increasing wall thickness, the stress state becomes biaxial. As a result, this method has only been applied for rings with ratios of radius to wall thickness greater than 9. The benefit of achieving a uniform compressive stress without any stress concentrations leads to a higher compressive strength compared with values measured on plates. The main drawbacks of this testing concept are the determination of failure stress and the maximum applicable compressive strain. For monotonic loading, it is also hard to achieve a fixed loading speed either in terms of strain or stress rate. No reports on fatigue testing in this manner could be found. Besides the problems, which arise under static testing, the unloading would be mainly driven by the elastic behavior of the composite ring, as long as no additional pressurization from inside the composite ring can be achieved. Also, the deterioration of the compliant ring and hysteretic heating can pose problems. In theory, the use of hydrostatic pressure of fluids could also be viable, but numerous new problems would arise using this concept. The most significant might be that by the use of tubes instead of rings, buckling could also occur before compressive failure. Tubes are necessary to achieve the necessary distance to the end caps and provide a decay length for a uniform stress distribution.

5.2. Axially Loaded Tubes

In the work of Davis, axially loaded tubes were used for the determination of the static compression behavior of glass- and boron-fiber reinforced epoxy in fiber direction. The loaded edges were reinforced with end caps comprising a groove in which the tube ends fit. A similar test setup is reported for static compression testing of unidirectional boron/aluminum tubes with fiber orientation along the loading axis. The problem of specimen failure near the end caps could not be overcome by shorter tubes or different end-cap material. A more recent use of axially loaded tube specimens can be found in Narsai et al. in their investigation of carbon-fiber reinforced epoxy with fibers oriented +35° to the loading direction. Compression loading of tubes with hoop wound fibers is a standardized method for static compression testing by ASTM D 5449/5449M. Tubes were also used to investigate the static compressive behavior of AS4/3501-6 towpreg tape in two layup configurations [±45/90/0]S and [±45/0/90]S. Buckling loads were determined to be very high, and in addition, an expanding collet was used inside the specimen to prevent buckling. The observed failure modes lacked transverse cracking, splitting, and delaminations. This observation is promising also for fatigue testing, as the development and growth of localized delaminations from the specimen’s edges are not possible due to the closed form. Similar to axially loaded flat specimens, end loading as well as shear or combined loading is possible. Typically, tubes also make use of tapered ends.

5.3. Concluding Remarks on Tubular Specimens

Tubular specimens can overcome the problem of stability as well as load introduction. In particular, for axially loaded tubes, the free-edge effect, which is reported to have significant influence on the fatigue life, can be excluded. The main disadvantage is that the scope of materials, which can be tested in this manner, is limited to materials, which allow for winding or braiding. Also problematic could be that for thicker cross sections, the necessary loads can increase rapidly.

6. Conclusion

A number of different testing methods are reported for quasi-static compression testing, for many of which an extension to compressive fatigue testing could be feasible but has so far
Table 1. Overview of pros and cons of compression testing methods with short gauge length.

| Group                  | Designation       | References                  | Pros                                      | Cons                                      |
|------------------------|-------------------|-----------------------------|-------------------------------------------|-------------------------------------------|
| Schematics in Figure 2 | Shear loading     | IITRI [7–9]                 | Versatile                                 | Highly sensitive to misalignment and pre-bended specimens |
|                        |                   | NBS [14–16]                 | Established testing procedures           | Tradeoff between critical buckling load and St. Vernant’s decay length |
|                        |                   | Celanese [8–10]             | Geat management for fatigue possible      | Width or thickness tapered specimens only possible with small cross-sectional variation |
|                        |                   | Hydraulic grips [17–19]     | Gauge length accessible                   |                                           |
| End loading            | RAE               | [25]                        |                                           |                                           |
|                        | DTRC              | [27]                        |                                           |                                           |
|                        | ELLS              | [20,26]                     |                                           |                                           |
|                        | Boeing mod.       |                             |                                           |                                           |
|                        | ASTM D 694        |                             |                                           |                                           |
| Combined loading       | CLC               | [29,30]                     |                                           |                                           |
|                        | NU fixture        | [24]                        |                                           |                                           |
|                        | MCL               | [23]                        |                                           |                                           |

Table 2. Overview of pros and cons of compression testing methods with long gauge length.

| Contact   | Group | References          | Pros                                      | Cons                                      |
|-----------|-------|---------------------|-------------------------------------------|-------------------------------------------|
| Schematics in Figure 5 | Surface | Full [31,32,38,39]  | Versatile                                 | Specimen heating                          |
|           | Window | [36]                | Width or thickness tapered specimen applicable | Potential second load path, due to friction |
|           | Edge   | [38]                | Size of reinforcement inhomogeneity can be larger (weave pattern) without affecting scattering | Supports can alter damage propagation (e.g., delay localized formation of delaminations) |
|           | Partial | [40]               |                                           |                                           |
| Contact   | Fix    | [21,41]             |                                           |                                           |
|           | Rollers | [43]               |                                           |                                           |
|           | Point  | [44]                |                                           |                                           |

Table 3. Overview of pros and cons of compression testing methods for nonstandard loading methods.

| Group                  | References | Pros                                      | Cons                                      |
|------------------------|------------|-------------------------------------------|-------------------------------------------|
| Schematics in Figure 1 | Three-point bending | [54,55]                   | Load introduction without stress concentrations | Small testing volume                      |
|                        | Four-point bending | [50,51,52]            | Heat management for fatigue testing possible | Stress gradient can lead to supporting effect |
|                        | Outside pressurized rings/tubes | [59]             | Gauge length accessible                     | Failure mode or sequence of failures hard to discern (e.g., delamination followed by compressive failure) |
|                        | Axially loaded tubes | [61–64]             | Load introduction without stress concentrations | Complex specimen manufacturing |
|                        | null       |                                           | Gauge length one-sided accessible         | Competing fatigue damage of core, face sheet failure and indentation of the face sheets |
|                        | null       |                                           |                                           | Temperature distribution can be different (especially for foam cores) |
|                        | null       | No stress concentrations, due to load introduction |                                           | Only wound or braided materials |
|                        | null       |                                           |                                           | Unloading defined by resiliency of composite |
|                        | null       |                                           |                                           | No direct stress determination |
|                        | null       |                                           |                                           | Maximum strain limited by compliant ring |
|                        | null       |                                           |                                           | Not tested for fatigue |
|                        | null       |                                           |                                           | Only wound or braided materials |
|                        | null       |                                           |                                           | High maximum force for thicker specimens |
not appeared in the Literature. In particular, work on compression–compression testing is sparse. It can be concluded that to perform such tests, much has to be known of the material in terms of mechanical properties to choose the correct testing method. It can be concluded that the axially loaded fatigue testing methods are the most versatile but show problems in terms of load introduction. These problems can partially be overcome by compression testing in a bending or tubular configuration. However, different failure modes, especially for bending tests in sandwich configuration, and manufacturing restrictions need to be considered. Therefore, the selection of the testing method for compression fatigue of fiber reinforced plastics is always a compromise of the required testing effort and perturbing effects, such as edge effects or inhomogeneous stress distribution and, therefore, accuracy of the results.

Table 1–3 provides an overview of the different testing methods discussed in this article along with their specific advantages and disadvantages.

Conflict of Interest
The authors declare no conflict of interest.

Keywords
composite materials, compression testing, fatigue testing, testing methods

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