TAILORING THE STRUCTURAL BEHAVIOUR OF A COMPOSITE GAS-FILLED SPRING DEVICE FOR A SWITCH IN POWER GRIDS

Fabian Folprecht[a], Tim Bätzel[a], Moritz Kuhtz[a], Paul Hoffeins[a], Matthias Gerlich[b],
Sebastian Spitzer[a], Maik Gude[a]

a: Technical University Dresden, Institute of Lightweight Engineering and Polymer Technology (ILK), Holbeinstr. 3, 01307 Dresden, fabian.folprecht@tu-dresden.de
b: Siemens AG, T REE ELM MES-DE, Otto-Hahn-Ring 6, 81739 München

Abstract: The shortest possible switching times are required to reduce voltage peaks and thus stabilise the power grids in the event of fluctuating renewable energy generation. Gas-loaded springs made of composite materials represent a promising design solution for this. Due to a complex geometry and anisotropic material behaviour, accompanying numerical analyses are required right at the beginning of the development process. In the present study, the deformation and failure behaviour of a composite spring is analysed by means of a parameter study based on a simplified geometry and load case as well as a combination of different materials and fibre angles. Subsequently, suggestions for the design and further development of the composite gas spring are derived.

Keywords: Composite gas spring, power grids, high-speed switches, tailored structural behaviour

1. Introduction

In AC-, DC- and AC/DC-hybrid-grids and their substations, circuit breakers are required to protect equipment like transformers and converters in case of peak voltages and currents resulting from overload or short-circuit [1,2]. Generally, circuit breakers include the main contacts and the operating mechanism as two main functional parts, where the operating mechanism moves the main contacts to open or close them. Thus, the main demand to this mechanism is to translate the mass posed by the main contacts along the switching distance within a specified switching time. Due to dynamic effects the switching time is massively influenced by the eigenfrequencies and the stored energy of the systems.

For the operating mechanism itself, various types are established: mechanical, hydraulic, pneumatic and combinations of them are most common [3]. Alternative mechanisms based on pyrotechnics and electromagnetics [4] can reach very fast switching times but feature the disadvantage of single use only (pyrotechnics) and need of electrical auxiliary equipment (electromagnetics). Mechanical spring mechanisms are the most common ones as they have the advantage of a simple, robust and cost-effective structure with less sensitivity to changing boundary conditions (e.g. temperature) and less inherent failure causes.

Due to changing grid topologies and growing amount of fluctuating renewable energy, shorter switching times in the range of a few milliseconds are required. This demand for higher energy and eigenfrequencies of the operating mechanism often cannot be fulfilled by purely mechanical spring systems like coil or cup springs. Thereby, the technical challenge of switching devices with very short shifting times is to tailor the stiffness both of the mechanical components of the drive unit and the passive components.

The approach of shifting eigenfrequencies to higher values though mass reductions achieved by the application of composite materials was successfully verified for coil springs [5,6] and volute springs [7]. Gas-pressure springs are an attractive alternative to coil and bellow springs. Since they have the potential to achieve a lower mass while maintaining the amount of potential energy. Moreover, this type of springs is readily available as sleeve type air springs. The main application of this design is high strokes that require high compliance, e.g. low wall thickness. However, the minimum wall thickness of the material is influenced by strength requirements, resulting in lower stored energy built up by internal pressure and low natural frequencies.

To increase the eigenfrequency, an encapsulated, leakage-free gas spring was introduced [9], which shows the ability to fulfill these requirements in combination with a simple and robust structure. This spring is based on a bellow structure with a steel sleeve. In order to further improve this type of gas spring, the approach of a composite structure is considered in this study due to excellent mechanical properties of fibre reinforced polymers.

In the study presented here, a numerical model for such springs is introduced based on a composite pressure cylinder. Therefore, an idealised geometry is used to compare different lay-ups and the material properties under combined inner pressure and axial loads. In this way, a deeper understanding of the underlying structural effects can be achieved and favourable configurations for further investigations can be identified. These findings provide an excellent basis for further developments to extend the results to more complex geometries.

2. Design concept

The metallic reference structure is shown in Figure 1 (left). The region of the bellow sleeve is about ca. 85 mm in diameter and 80 mm in active deformed length. This prototype reaches a maximum of 9 mm overall deformation in axial direction and can be operated at 100 bar. In case of switching, the stored energy is transferred to the contact by a conversion to a longer path. For a further development of the reference spring to a composite spring structure, an increase of transferring energy is needed. This can be achieved both by increasing the inner pressure for higher output forces and by increasing the displacement. Though, the mass of the structure is intended to not raise with respect to an increase in the eigenfrequency of the spring.

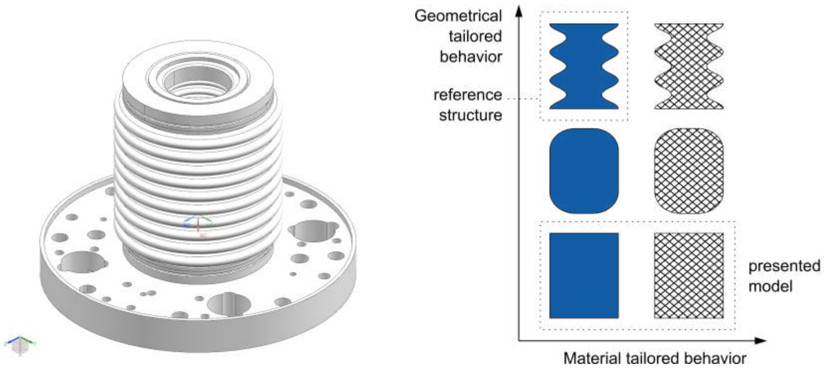


Figure 1: Metallic reference structure of the bellow gas spring (left) and tailored deformation behaviour by the geometric and material design (right)

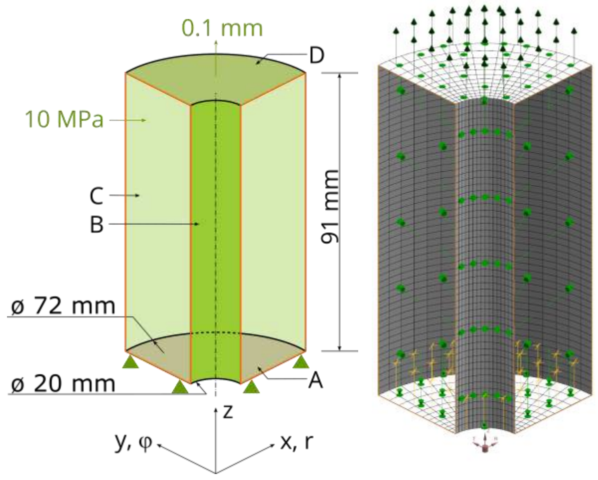
For composite gas-loaded bellow springs considered in this study there are two basic design elements, which allow a tailored deformation behavior. Adjustments of the relation between pressure resistance and maximum axial stroke are supported by the geometric design of bellow arches and laminate architecture of the bellow material.

The utilisation of fibre-reinforced materials introduces layerwise fibre orientations as additional design parameters and, thus, offers an extended design space. The bellowed design allows for tailored load-dependent stiffness within the gas-spring structure. Through the individual geometry and total number of bellow arches, the structure's axial flexibility can be adjusted as needed for the special application, while maintaining the tangential stability high for internal pressure load capability. Still, those characteristics are interacting with each other.

In a first step, the structural behaviour under internal pressure loading and additional axial stretching as a function of the prevailing fibre orientation is the subject of the numerical investigations. While the numerical studies are focused on a representative cylindrical structure, there are additional geometrical effects to be considered for the application-oriented bellow structure. A detailed investigation of the cylindrical structure will grant a deeper understanding of underlying structural effects.

3. Numerical analysis of the deformation behaviour

The deformation behaviour of the substitute structure is investigated by means of a finite element model. A linear quasi-static model is created using the Siemens Simcenter 3D software. Figure 2 shows the geometric dimensions and the boundary conditions as well as the numerical representation as a substitute model.



Model information
Simcenter Nastran Structural Linear steady state
1984 4-node shell elements
Base and top surface (A,D): Steel
Shell surfaces (B,C): Laminate

Figure 2: Schematic representation of the dimensions and boundary conditions (left, centre) and key information of the FEA model (right)

The base and top surfaces of the cylinder ring are represented as a 10 mm thick steel shell. The shell surfaces are modelled as a six-layer, balanced and asymmetrical angle ply laminate with lay-up $[\alpha/\text{-}\alpha]_3$. Since the wall thickness is expected to have a significant influence on the stiffness of the subsequent bellows via the Steiner proportion, this is taken from the metallic reference structure. The cylinder is supported at its base surface A in the *z*-direction. The quarter model of the cylinder is supported in the symmetry planes with symmetry boundary conditions. A pressure load boundary condition of 10 MPa is applied to the interior of the cylinder ring (surfaces A to D). In addition, the top surface D is displaced up to 0.1 mm in the positive *z*-direction. The deformation is calibrated by an equal model with a steel jacket up to materials yield stress.

In a preliminary investigation, the influence of the symmetry boundary conditions was investigated. Due to the asymmetric layer structure, a coupling between in-plane loads and out-of-plane deformations existed according to classical laminate theory. The difference of the resulting deformations of a full model and a quarter model are very small, which is why the quarter model is chosen as reference model. Secondly, the influence of the solver was investigated by applying a solution in one solution step and in 20 solution steps. The resulting deformations and the corresponding stresses are higher in the model that was solved in one solution step. Since this corresponds to a more conservative design, this solution procedure is chosen as reference.

The failure behaviour is evaluated in post-processing by means of a user-defined material model according to the failure mode concept of Cuntze [8], that enables both a fracture mode-related and a cumulative evaluation of the ply-by-ply failure behaviour. According to the principle of St. Vernant, only the elements located in the undisturbed area of the laminate are used for evaluation.

Two different composite materials are analysed. On the one hand carbon fibre reinforced polymer (CFRP) HexPly8552 (*CF-EP)* and on the other hand glass fibre reinforced polymer GFRP Silenka E-Glass with MY750/HY917/DY063 are investigated. A linear-elastic material behaviour is assumed for both materials. The characteristic values are taken from the ESAComp-Database.

The results for the model with CF-EP material are compiled in Figure 3. For fibre angles of 40° or greater, the model calculates a failure index of less than 1 for all load cases investigated and, thus, testifies a basic suitability of this material for the loading profile.

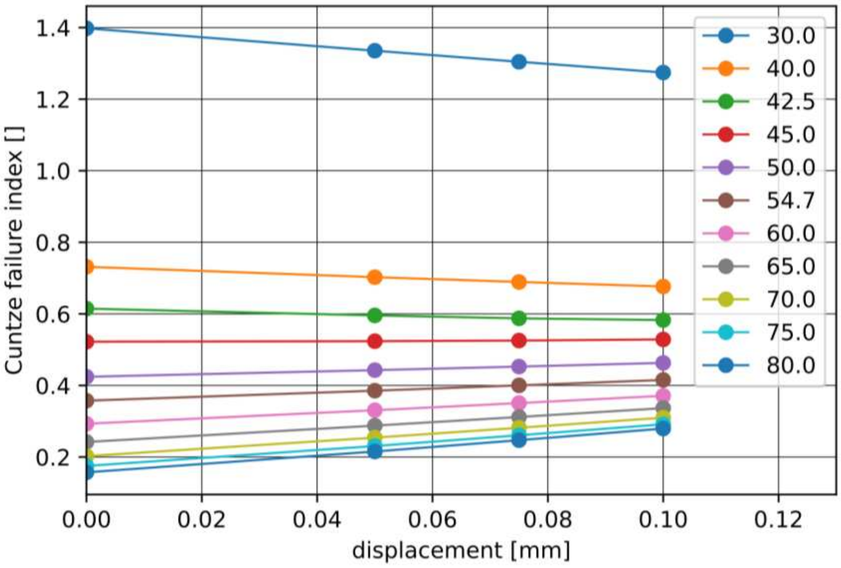


Figure 3: Failure index of the CF-EP Hex8552 dependent of the fibre angle

While ±54.7° fibre angles are optimal for cylindrical areas in conventional pressure tanks, the introduced model exhibits a decreasing failure index with increasing fibre angles for the first loading stage (internal pressure only). This effect is due to the constrained axial displacement at the base and cover plate (cf. A, D in Figure 2), which result in only tangential stresses acting upon the jacket area.

As expected, the application of positive axial strain results in rising Cuntze failure indices for fibre angles of ±50° or above. However, calculations involving fibre angles below ±45° revealed descending failure indices with increasing axial strains. This can be accounted for by the failure envelope’s shape in the stress space. Through axial loading, resulting principle stresses are progressively aligned with the fibre axes, leading to decreased failure indices.

The transition between increasing and decreasing failure index due to axial strain occurs at slightly less than ±45°

As illustrated by Figure 4, this structural behaviour was observed for the glass fibre-reinforced cylinder model as well. Compared to the CFRP structure, the material utilisation is significantly higher and none of the calculated layer structures achieves a failure index below 1. This clearly outlines the inferior material strengths of GFRP.

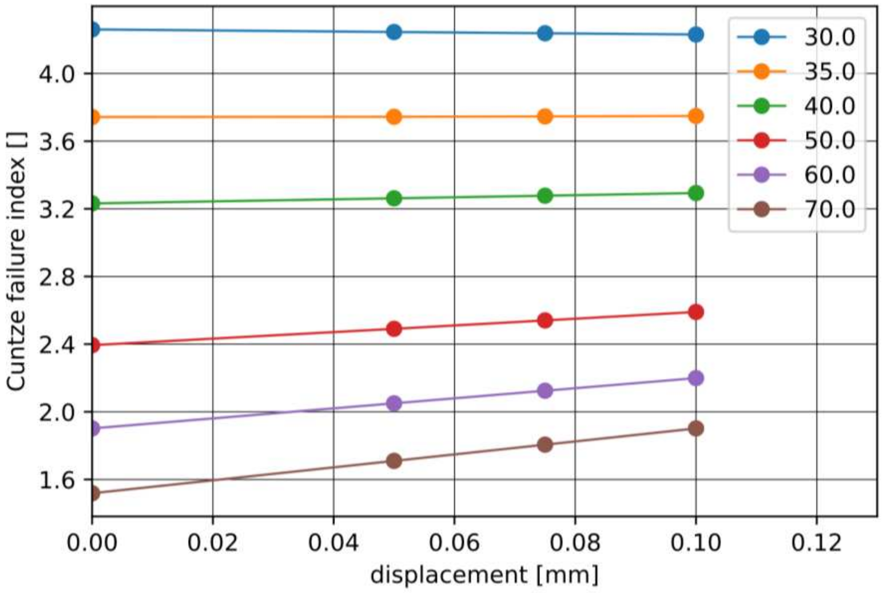


Figure 4: Failure index of E-Glass with MY750/HY917/DY063 dependent of the fibre angle

Corresponding to the calculation with CFRP material, the model exhibits a similar variable behaviour under applied axial strain. The transition from decreasing failure indices (for lower fibre angles) to increasing failure indices (for higher fibre angles) occurs at approximately ±35°, 10° lower than for CFRP material.

4. Interpretation of the results

Due to the axial support of the cylinder model at the end faces, the initially prevailing stress state is decisively characterised by tangential stresses. This is outlined by lower failure indices for higher fibre angles at zero axial strain (Figure 3, Figure 4). The applied axial displacement causes the build-up of axial stresses in the jacket area. This redistribution of the axial load causes the axes of the principal stresses to shift increasingly in the axial direction.

For the case of a free displaceable top surface, a principal stress ratio of 2:1 (typical ration for internally pressurised hollow bodies) is established in the jacket area and the principal stress axes are oriented at 54.7°. Based on net theory (basic assumption: equilibrium of forces inside single plies), the lowest material utilisation is achieved for the case of aligned principal stress axes and fibre orientations. Based on this approach, the observed failure indices history obtained in the numerical study can be explained through the axial straining. If principal stress axes converge with fibre orientations through the allowance of axial strain, the failure index falls. If both orientations diverge, the failure index increases.

The results for CFRP contain fibre angles that are constantly below a Failure Index 1 in the deformation range considered and exhibit a decreasing failure index for increasing deformation. Compared to the metallic reference, which was used to calculate the maximum axial elongation the numerical study (elongation at which the metallic material's yield stress was reached), these findings suggest a larger possible stroke without structural failure. Suitable non-linear model with higher axial strains are necessary to validate this relationship.

The model presented corresponds to a global view and is not able to consider local effects. This is mainly due to the cylindrical geometry, which does not include the bellows with corresponding local effects. Figure 5 (left) illustrates an exemplary section of the bellow. The effects involving axial and tangential stresses (discussed above) are expected in a similar way for complex bellow structures due to the fundamentally analogous internal pressure load with successively released axial strain. However, this underlying mechanism is likely to be superimposed by further geometry-based effects, as well as dynamic effects. Thus, additional forces and moments act locally on the individual shafts (cf. Figure 5, centre). This is expected to result in local deformations in terms of bending of the single bellows as shown in Figure 5 (right).

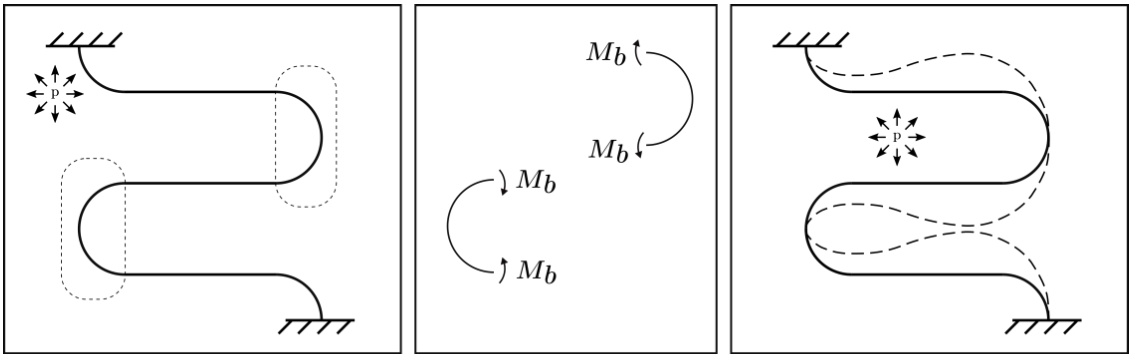


Figure 5: Exemplary bellow structure (left) internal cutting forces in inner and outer bellow (centre) expected local deformation of the bellow structure (right)

Bending deformations in the bellow jacket area are expected to induce tensile and compressive stresses in the composite layup, especially in layers close to both surfaces. Thus, stresses similar to the tension- and compression-loaded cylinder jacket may be the result. Future in-depth investigation is necessary to clarify if it is possible to transfer the effect of decreasing failure indices through increasing axial strain from cylindrical jacket structures to bellowed jacket structures. At this point, the influence of different laminate thicknesses in correlation with normalized bending strengths are to be considered.

5. Conclusion

Basic investigations for the transformation of an existing gas-filled spring device into a composite spring were presented. A tailored deformation behaviour is crucial to meet given requirements. Exploitable design variables are based on two approaches: the geometric structure and the composite material structure. Within the scope of the paper, the material structure was first investigated. On this behalf, a linear simulation model was developed and the suitability of CFRP and GFRP materials with different fibre angles for a balanced angle ply laminate were investigated. Under constant internal pressure, different axial deflections were considered. The laminate strength was evaluated according to the Cuntze failure criterion.

The CFRP material was found to be particularly suitable for the structure under consideration. For balanced angular composites with fibre orientations of <±45° for CFRP and <±35° for GFRP, the failure index also decreases with increasing axial deflections. Thus, it is expected that the feasible axial deflection is significantly increased compared to the metallic structure. This relationship is to be validated in a non-linear model with large deflections. Finally, the transfer of the results to the bellow structure was discussed. At this point, additional local effects are expected, which must be investigated and validated through the implementation of more comprehensible simulation models.

6. Acknowledgement

The work took place as part of the project "Leichtbautechnologien in lebensphasenübergreifenden Kreislaufprodukten der Energiewende" (LiKE, funding code 03LB2008G). The project is funded as part of the technology transfer program lightweight design of the Bundesministerium für Wirtschaft und Klimaschutz BMWK and supported by Projektträger Jülich.

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

7. References

1. Jürgen Häfner, Björn Jacobson. Proactive Hybrid HVDC Breakers – A key innovation for reliable HVDC grids. Electric power systems of the future – Integrating supergrids and microgrids. International Symposium in Bolgna, Italy 13-15 September, 2011
2. Marius Langwasser, Giovanni De Carne, Marco Liserre. Requirement Analysis of Circuit Breakers in Future Hybrid AC/DC Grids. PCIM Europe 2019; International Exhibition and

Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management

3. Hiroki Ito. Switching Equipment. International Council on Large Electric Systems (CIGRE) Study Committee A3: High Voltage Equipment. Springer
4. Christian M. Franck. HVDC Circuit Breakers: A Review Identifying Future Research Needs. IEEE Transactions on Power Delivery. Volume: 26, Issue: 2, April 2011
5. DE102011018217A1 – Hufenbach, Lepper, Werner: „Verfahren zur Herstellung von Federelementen aus Faserverbundwerkstoffen“
6. DE102012112937A1 – Lepper, Werner, Köhler, Bartsch, Hufenbach: „Vorrichtung und Verfahren zur Herstellung einer Feder aus Faserverbundwerkstoff“
7. Martin Petrich, Ulft Kletzin, Tom-Luis Weimann, Julius Feld: Carbon-Evolutfeder. Draht Bd 72 (2021), 6, p.38, Bamberg: Meisenbach, 2021.
8. Cuntze, R. G.; Freund, A.: The predictive capability of failure mode concept-based strength criteria for multidirectional laminates. Composites Science and Technology 64 (2004), pp. 343-377.
9. DE102019219728A1 – Ebelsberger, Gerlich, Schacherer: "Elektrische Schalteinrichtung"