ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

ORIGINAL ARTICLE

eurosteel AMSTERDAM 2023

Ernst & Sohn A Wiley Brand

Optimisation of the damping properties of steel structures using adhesively bonded joints

Jannis Damm[1] | Matthias Albiez[1] | Thomas Ummenhofer[1]

Correspondence

Dr.-Ing. Jannis Damm
Karlsruhe Institute of Technology (KIT)
Steel and Lightweight Structures
Otto-Amman-Platz 1
76131 Karlsruhe
Email: jannis.damm@kit.edu

[1] Karlsruhe Institute of Technology (KIT), Steel and Lightweight Structures, Karlsruhe, Germany

Abstract

Adhesives offer both good damping properties and very high strengths. The possibilities for using the positive damping properties in particular to optimise dynamically stressed steel structures have rarely been explored to date. In this paper, comprehensive numerical and experimental investigations are presented. In numerical investigations on dynamically loaded, representative steel structures, the potential for damping of structures by adhesively bonded joints is analysed. Numerical investigations show that the vibration amplitudes of adhesively bonded structures are more than 95 % lower than those of welded reference structures in the relevant resonance case. Based on this, the damping properties of adhesively bonded tubular steel joints in a scale relevant for construction industry were experimentally investigated. Different geometry and test boundary conditions are investigated in a parameter study. The loss factor of tubular joints is a maximum of 0.38, which is relevant for steel construction. Based on the results of experimental investiga-tions, a methodology is presented for the analytic determination of the damp-ing properties of adhesively bonded tubular joints for various specimen ge-ometries and stress boundary conditions. For this purpose, dimensional anal-ysis is carried out using the Buckingham Pi Theorem.

Keywords

Adhesive damping, adhesively bonded tubular steel joints, structural damp-ing, steel structures, dynamics, Buckingham Pi Theorem, dimensional analy-sis, loss factor

1 Introduction

Building structures like bridges, towers etc. are often exposed to dynamic loads. This can cause structural vibrations. A variety of problems can result from uncontrolled vibration phenomena, which negatively affect both the load-bearing capacity and the serviceability of structures. Viscoelastic adhesives based on polyurethanes and epoxy resins offer very good damping properties in addition to high strength. Up to now, these damping properties have primarily been investigated on the basis of numerical and analytical observations of test specimens on a small component scale [1; 2]. Therefore, the investigation of the damping properties of adhesively bonded joints on a scale relevant for steel constructions was the subject of FOSTA research project P 1272 [3].

1.1 Scope of this paper

The results of the research presented in this paper are based on the work presented in [3; 4]. The focus of the paper is on the one hand on numerical analyses of the potential for optimising the dynamics of steel structures by adhesively bonded joints. Here, different steel structures with variable geometrical dimensions and material properties of the adhesives are taken into account. On the other hand, the results of experimental investigations of the real damping properties of different types of adhesively bonded joints on large-scale with variation of different geometric and material parameters are presented. In the present paper the focus is on adhesively bonded tubular steel joints. Based on this, the results of further work of the corresponding author [4] on the development of methods for the graphic-based prediction of the damping properties of bonded joints in the context of the practical design of steel structures were derived are presented.

2 Materials

2.1 Adhesives

Comprehensive characterisation tests were carried out on a total of five adhesive systems to select the adhesives based on the requirements of steel construction, including the mechanical properties, the necessary processing conditions and the temperature range to be applied. The tests took place at the LWF of the University of Paderborn [3]. Based on the test results, the epoxy–resin hybrid-based 2-component adhesive Sikadur F51-60 (referred to as adhesive EPH) from SIKA AG® and the semi-structural 2-component polyurethane adhesive Körapur 842 (referred to as adhesive PUR) from Kömmerling Chemische Fabrik GmbH® were selected for further investigations. Essential mechanical properties of the EPH and PUR adhesives, which were determined on the basis of tensile tests on bulk samples, are summarised in table 1. The results of the adhesive characterisation are shown in detail in [3; 5].

Table 1 Mechanical properties of the adhesives EPH and PUR (Modulus at 1% elongation, loss factor at room temperature and excitation at 1 Hz) [4]

	Adhesive EPH	Adhesive PUR
Young's modulus	86 MPa	356 MPa
Poisson's ratio	0.42	0.41
Loss factor at room temperature	0.11	0.50

2.2 Steel

The circular hollow sections used for manufacturing the experimentally investigated tubular joints consist of steel of the grade S355J2H according to DIN EN 10210–1 [6]. The base material of the steel profiles has a yield strength of 355 MPa and a tensile strength of 490 MPa, according to DIN EN 1993-1-1 [7]. Young's modulus is 210,000 MPa. These material properties are also used in the numerical simulations.

3 Numerical investigations

The numerical investigations serve to identify the potential of adhesively bonded joints for optimising the dynamic behaviour of representative steel structures by varying geometric and material parameters. In addition, the aim is to derive knowledge on the influence of the investigated parameters on the damping properties of adhesively bonded structures, which can be applied in the context of practical structural design. The investigations include both statically determined systems with an adhesively bonded joint and statically indetermined systems with multiple adhesively bonded joints. In the following, exemplary results of investigations on the influence of the implementation of adhesively bonded joints as well as the associated adhesive-inherent damping on the structural dynamics of an observation tower in hollow-section framework construction are presented. In particular, the influence on the height of the first natural frequency as well as the resonance amplitudes due to harmonic excitation are analysed.

3.1 Model

The structure of the observation tower is created as a combined beam and solid model (see Figure 1). The tower has a height of 35.0 m. The distance between the legs is 15.0 m at the base and 8.0 m at the top. In order to represent the mass of an observation platform, a point mass of 20 tons is placed at the top of the tower structure. The adhesively bonded joints of legs and bracings of the framework consist of solid bodies that are connected with beam elements. The design of the adhesively bonded joints shown in Figure 2 is based on the design principle of adhesively bonded bracing joints of jacket framework structures of wind turbines investigated in [8; 9]. The joints consist of a multi-part tubular sleeve which completely encloses the legs. The individual parts of the ring sleeve are joined by welding or screwing. The bracings are welded to the tubular sleeve. The resulting joint gap between the tubuluar sleeve and the legs with a thickness of 10 mm is adhesively bonded.

The material properties of the steel materials and the adhesives are in a first stepimplemented as linear-elastic according to Table 1, what is assumed to be sufficient for the purpose of a potential analysis. In addition, the damping properties of the materials are implemented. To take into account the damping properties of the steel material S355, a loss factor of η_{steel} = 0.0002 [10] is defined. Exemplary loss factors between 0.1 and 0.3 are considered for the adhesives EPH and PUR.

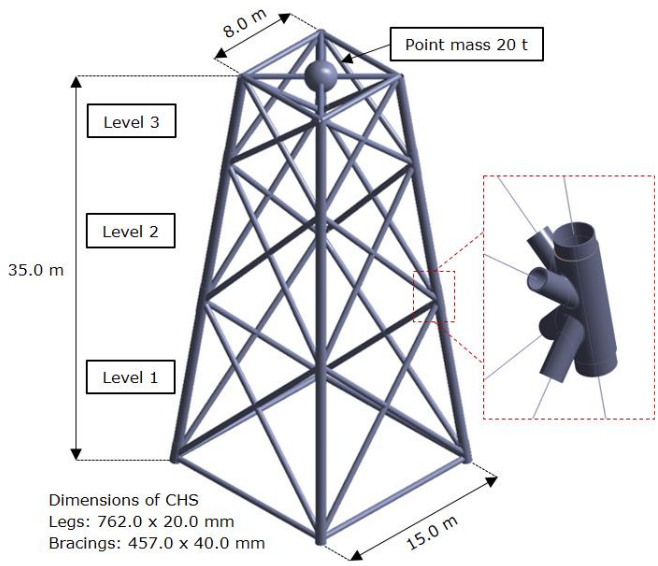

Figure 1 Numerical model of the observation tower in hollow section framework construction with adhesively bonded joints of the bracings based on [11]

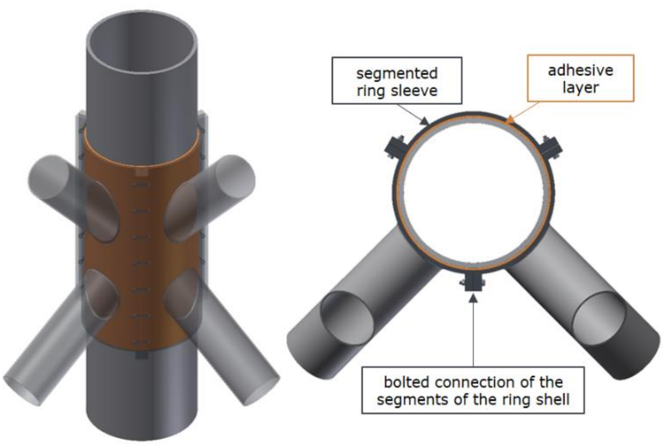

Figure 2 Design concept of the hollow section framework structure with adhesively bonded bracings based on [8]

3.2 Eigenmodes and eigenfrequencies

In the works by Albiez et al. [8], it was shown that the global load-bearing behaviour of framework structures is only negligibly influenced by the implementation of adhesively bonded joints. This applies independently of the adhesive stiffness. Using a modal analysis, it can be shown that this also applies to the structural dynamic properties of a framework structure in the form of the first natural frequency.

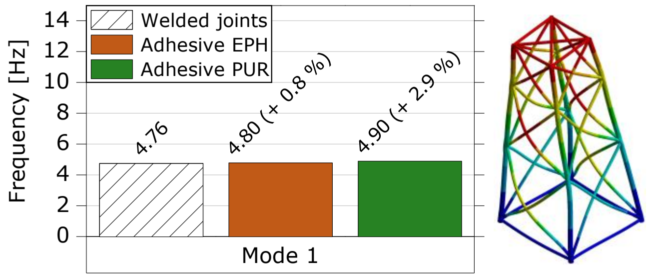

Figure 3 Comparison of the natural frequencies of modes 1 of the systems with welded as well as adhesively bonded joints based on [4]

Figure 3 shows the natural frequencies of a welded reference structure and two adhesively bonded structures made with the adhesives EPH and PUR. It can be seen that the natural frequencies of the adhesively bonded structures increase slightly compared to the welded reference structure. Assuming an approximately constant mass, this can be explained by the higher joint stiffness of the adhesively bonded joints shown in Figure 2 compared to conventionally welded joints.

3.3 Frequency response analysis of stationary vibration states

For dynamically stressed structures, the resonance case is particularly critical, because occurring amplitudes are limited only by existing damping.

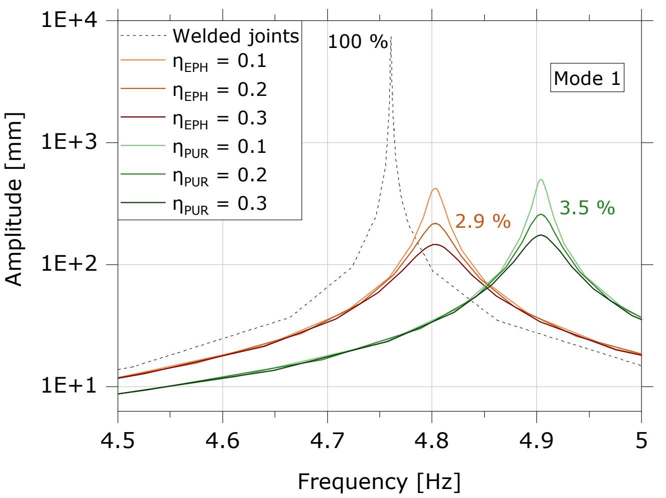

Figure 4 Comparison of the oscillation amplitudes as a result of resonance excitation in the range of mode 1 of the systems with welded as well as adhesively bonded joints based on [4]

Thus, a frequency response analysis is carried out to evaluate the influence of adhesively bonded joints on the dynamic response in the resonance range of mode 1. Figure 4 shows a comparison of the oscillation amplitudes in the range of the first natural frequency of the welded structure and of structures with bonded joints with different adhesive loss factors.

It is shown that the resonance amplitudes decrease significantly by implementing adhesively bonded joints compared to the welded reference structure. For a loss factor of 0.2, the resonance amplitudes of the adhesively bonded structures are only 2.9 % (EPH) and 3.5 % (PUR) of the welded reference structure, respectively. The amplitude decrease depends on the Young's modulus and the loss factor of the adhesive. It is shown that the resonance amplitudes decrease significantly by implementing adhesively bonded joints compared to the welded reference structure. The influence of damping on the resulting amplitudes is greater for lower Young's modulus and higher loss factors of the adhesive. The reason for this is the higher deformation of the adhesive layer due to lower adhesive stiffness, which in combination with generally higher damping properties of the adhesive lead to higher energy dissipation. Summarising, the numerical investigations show the high potential of adhesively bonded joints to improve the dynamic behaviour of steel structures. Nevertheless, an important prerequisite for the use of the damping properties of bonded joints and connections within the context of numerical calculations is first of all their experimental determination. This is the subject of the following section.

4 Experimental investigations

The damping properties of adhesively bonded tubular joints are determined under variation of different geometries and test boundary conditions using dynamic hysteresis tests. As shown in Figure 5, the test specimens consist of two circular hollow sections that are inserted into each other and subsequently joined by adhesive bonding. The dimensions of the inner hollow section are kept constant, whereas the dimensions of the outer hollow profile are varied. This enables the investigation of three different, practically relevant adhesive layer thicknesses. In addition, two overlap lengths are investigated (Figure 5).

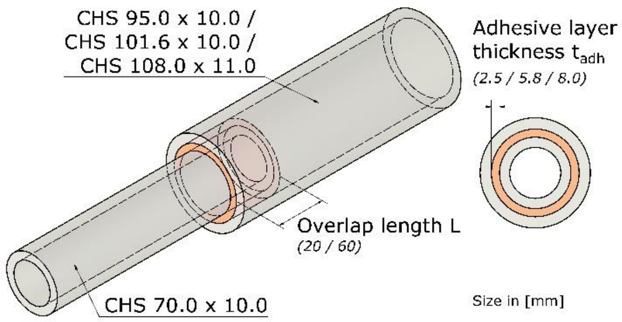

Figure 5 Investigated dimensions of adhesively bonded tubular joints based on [4]

4.1 Dynamic hysteresis tests

The dynamic tests are performed as hysteretic tests under alternating tension-compression load to avoid creep deformations. The test setup of the dynamic tests is therefore designed in such a way that no slip occurs within the test specimen, between the bonded components and the connection of the test specimen to the testing machine while changing the load direction from tension to compression and vice versa. The test setup used for the dynamic tests is shown in Figure 6. A schematically representation of an adhesively bonded tubular joint and the components connecting the specimen to the testing machine coloured in blue-grey is shown left in Figure 6. The specimens are connected to the servo-hydraulic testing machine by cylindrical thread inserts, which are inserted into the openings of the circular hollow sections at both end of the specimen. CHS and the insert are connected by a bolt. The bolt is pushed completely through the circular hollow section and the cylindrical insert. The bolt is then pre-tensioned between the circular hollow profile and the insert by screwing two ring-shaped nuts onto the external thread of the insert [12].

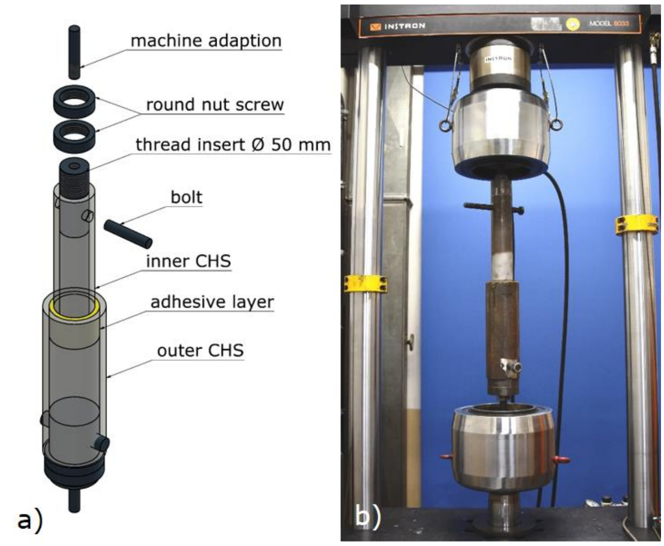

Figure 6 a) Schematic representation of a adhesively bonded tubular joints and the components for adapting the specimen to the testing machine (coloured blue-grey), b) Test set-up of the dynamic tests on adhesively bonded tubular joints based on [4; 12]

The tests are performed in two different test levels. These differ in the applied shear strain. In test level A, a maximum shear strain of 2 % is applied, for which the adhesive layers are still approximately in the linear viscoelastic range. In test level B, the maximum shear strain is 8 %. The influence of nonlinearities increases significantly compared to test level A. In each test level three different test frequencies (1 Hz, 3 Hz, 5 Hz) were examined. The loss factor is used as a parameter for analysing the damping properties. This can be determined using a time-based evaluation from the time offset between an excitation signal (machine force) and a response signal (machine displacement). Additionally an energy-based approach can be used, where stored and dissipated energy per cycle are determined [12].

4.2 Test results

Figure 7 shows exemplary shear stress-shear strain hystereses for tubular joints with adhesive layer thickness 5.8 mm and overlap length 20 mm in test level A and B. It can be observed that the dissipated energy, which corresponds to the area of the hysteresis, rises with increasing shear deformation of the adhesive layer. Furthermore, a reduction in specimen stiffness with increasing shear strain can be observed. This can be explained by the nonlinear deformation behaviour of the adhesive. The loss factors determined from the hystereses shown are also given in Figure 7. In both test levels, the loss factor determined is in a relevant range for steel construction [4; 11]. In addition, the loss factor increases significantly with increasing shear strain.

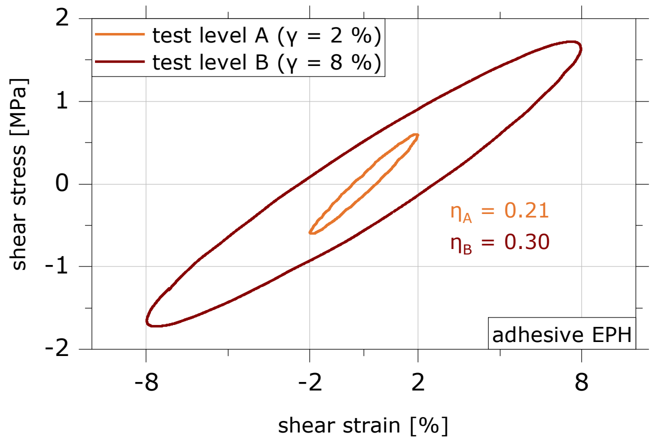

Figure 7 Exemplary shear stress-shear strain hystereses for tubular joints with adhesive layer thickness 5.8 mm and overlap length 20 mm in test level A and B for frequency 1 Hz based on [13]

In Figure 8 exemplary results of the dynamic hysteresis tests for tubular joints made with adhesive EPH with overlap length 20 mm and different adhesive layer thicknesses in test level A and B are presented in terms of the determined loss factors.

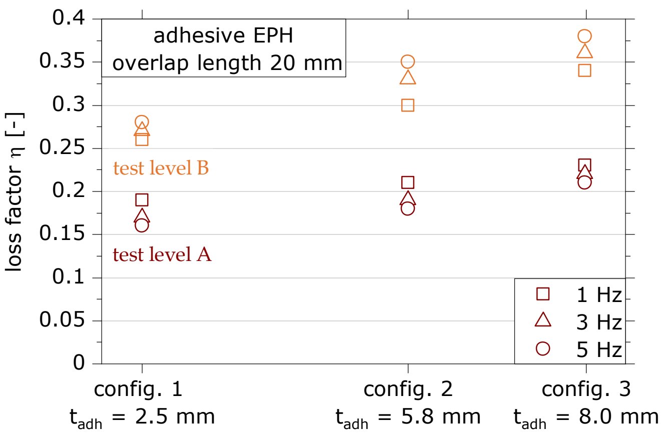

Figure 8 Exemplary results of the dynamic hysteresis tests for tubular joints with overlap length 20 mm in test level A and B based on [4]

The results in Figure 8 initially confirm an increase in damping with rising stress in the adhesive layer for all adhesive layer thicknesses. Furthermore, an influence of the test frequency on the loss factor can be observed. In test level A, the loss factor decreases with increasing frequency for the same geometry of the specimens. In test level B, an inverse influence of the test frequency on the damping properties can be observed, which can be justified by a change in the polymer structure of the adhesive with increasing deformation. Increasing the adhesive layer thickness has a positive effect on the damping properties of adhesively bonded joints. In both test levels, an approximately linear relationship can be observed between the loss factor and the adhesive layer thickness. The investigations have also shown that increasing the overlap length has a negative effect on the damping properties. This finding is almost independent of the adhesive layer thickness as well as the amount of stress on the adhesive layer [4].

5 Analytical description

5.1 Basics of dimensional analysis

The objective of the dimensional analysis is the determination of a functional relationship of the test results. In the first step, all identified factors that have an influence on the defined target value (here loss factor) are summarised. Dimensionless parameters are then formed from the identified factors. This is done by combining the influencing factors in a reasonable way according to the Buckingham Pi theorem. If the results of conducted tests are plotted over a combination of all dimensionless parameters, the functional correlations of these test results can then be described analytically. The most reasonable combination of all dimensionless parameters can be determined iteratively or on the basis of empirical values. The identified functional relationships can then be described by simple regression functions.

5.2 Identification of functional relationships of the results of dynamic tests on tubular joints

Experimental investigations have shown that the damping properties of adhesively bonded tubular joints depend on both geometric and stress boundary conditions. The geometric influencing variables are the adhesive layer thickness (t_{adh}), the overlap length (L) and the adhesive layer width in the form of the average circumference of the adhesive layer (U_m). Furthermore, the test frequency (f) and the amount of shear strain (γ) influence the damping properties. The loss factor is the value to be described.

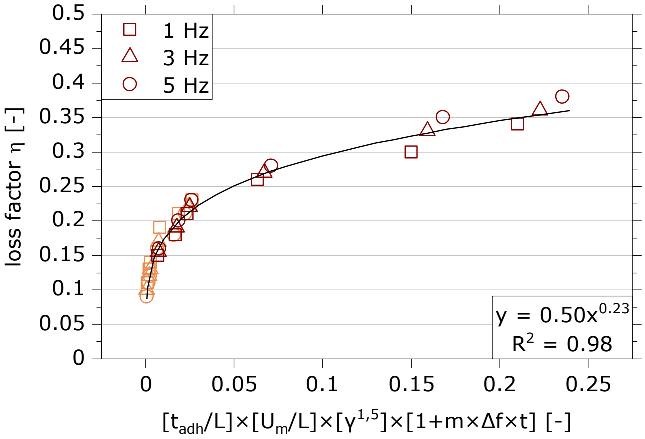

Figure 9 Dimensionless visualisation of the results of the experimental investigation of tubular joints made with the EPH adhesive and their analytical approximation by an exponential regression function based on [4]

From the identified influencing variables, 4 dimensionless parameters can be determined according to the principles of the Buckingham Pi theorem. These can be combined using known correlations in such a way that the expression shown on the x-axis in Figure 9 is produced. The parameter m takes into account the shear strain-dependent frequency influence of the adhesive.

The test results can then be plotted in a diagram as a function of all test boundary conditions [14]. The functional relationships of all the test results shown can be determined by dimensional analysis. An analytical determination of the loss factor, taking into account all identified influencing factors, is enabled by derived regression functions with a high coefficient of determination ($R^2 = 0.98$) [4].

6 Summary and Conclusions

Numerical investigations show that the damping properties of steel structures can be significantly improved by implementing adhesively bonded joints. An influence of the adhesively bonded joints on the natural frequencies of the structures cannot be observed. In the resonance case, amplitude reductions of more than 95 % can be achieved compared to conventionally welded structures. Adhesives with low modulus of elasticity and high loss factor are particularly suitable. From a practical construction point of view, loss factors > 0.1 should be prioritised.

Experimental investigations on the experimentally determinable damping properties of adhesively bonded tubular joints show that the loss factor of the investigated test specimens are always in a practically relevant order of magnitude and are up to 0.38 at the maximum. An analysis of the influence of the geometry parameters of the investigated test specimens shows that the damping properties of adhesively bonded tubular joints can be enhanced especially by increasing the adhesive layer thickness and reducing the overlap length. It follows that the structural design of adhesively bonded joints of dynamically stressed structures must be considered against the background of the geometric dimensions of the adhesive layer.

Finally, a method is presented which allows to describe test results in form of a functional relationship that is easy to describe, independent of geometry and test boundary conditions. The developed methodology offers the advantage that the damping properties of bonded test specimens can be determined on the basis of a small number of tests, even for non-investigated test and geometry boundary conditions.

The development of numerical material models which contain the damping properties of the adhesives is often very complex. Experimental investigations are also required to validate the models. For a practical design of structures, these procedures are too complex and often cannot be implemented by the designing engineer. A graphic-based prediction of the damping properties of bonded joints represents an efficient engineering approach. Therefore, the developed method forms the basis for the consideration of the damping properties of adhesively bonded joints, taking into account defined validity limits in the context of the practical design of structures [15]. Future research has to adress complex stress states and the influence of geometrical and material nonlinearities as well as temperature on the damping properties.

Funding
The project IGF 20080 N (FOSTA P 1272) of the Forschungsvereinigung Stahlanwendung e.V., Sohnstraße 65, 40237 Düsseldorf, is supported by the Federal Ministry for Economic Affairs and Climate Action through the German Federation of Industrial Research Associations (AiF) as part of the program for promoting industrial cooperative research.

We thank our research partners Laboratory for material and joining technology (LWF), University of Paderborn and Institute of Mechanics (IfM), University of Kassel.

References

[1] Almitani, K. H.; Othman, R. (2016) *Analytical solution of the harmonic response of visco-elastic adhesively bonded single-lap and double-lap joints* in: International Journal of Adhesion and Adhesives 71, pp. 55–65. https://doi.org/10.1016/j.ijadhadh.2016.08.004

[2] da Silva, L.; Öchsner, A.; Adams, R. D. [Hrsg.] (2018) *Handbook of adhesion technology*. Cham, Switzerland: Springer.

[3] Damm, J. et al. (2022) *Experimentelle und numerische Untersuchung der Dämpfungseigenschaften geklebter Strukturen unter dynamischer Beanspruchung – Dämpfende Knoten (FOSTA P 1272, IGF Nr. 20080 N)*.

[4] Damm, J. (2023) *Zum Dämpfungsverhalten viskoelastischer Klebverbindungen im Stahlbau* [PhD thesis]. Karlsruhe Institute of Technology (KIT).

[5] Göddecke, J. et al. (2023) *Experimental investigation and numerical modelling of the damping properties of technological bonded joints* in: The Journal of Adhesion (In submission).

[6] DIN EN 10210-1 (Juli 2006) *Warmgefertigte Hohlprofile für den Stahlbau aus unlegierten Baustählen und aus Feinkornbaustählen – Teil 1: Technische Lieferbedingungen*. Berlin: Beuth Verlag GmbH.

[7] DIN EN 1993-1-1 (Dezember 2010) *Eurocode 3: Bemessung und Konstruktion von Stahlbauten – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau*. Berlin: Beuth Verlag GmbH.

[8] Albiez, M. et al. (2022) *Hybrid joining of jacket structures for offshore wind turbines – Determination of requirements and adhesive characterisation* in: Engineering Structures 259, pp. 114186. https://doi.org/10.1016/j.engstruct.2022.114186

[9] Albiez, M. et al. (2022) *Hybrid joining of jacket structures for offshore wind turbines – Validation under static and dynamic loading at medium and large scale* in: Engineering Structures 252, pp. 113595. https://doi.org/10.1016/j.engstruct.2021.113595

[10] Niehues, K. K. (2015) *Identifikation linearer Dämpfungsmodelle für Werkzeugmaschinenstrukturen* [PhD thesis]. Technische Universität München.

[11] Damm, J.; Ummenhofer, T.; Albiez, M. (2022) *Influence of damping properties of adhesively bonded joints on the dynamic behaviour of steel structures: numerical investigations* in: The Journal of Adhesion 98, H. 7, pp. 934–962. https://doi.org/10.1080/00218464.2020.1865161

[12] Damm, J. et al. (2023) *Experimental and numerical investigation of the damping properties of adhesively bonded tubular steel joints* in: The Journal of Adhesion. https://doi.org/10.1080/00218464.2023.2178909

[13] Damm, J. et al. (2021) *Dämpfungseigenschaften geklebter Verbindungen – Simulation und Validierung an Bauteilversuchen* in: adhäsion KLEBEN & DICHTEN 65, H. 10, pp. 32–45. https://doi.org/10.1007/s35145-021-0530-6

[14] Buckingham, E. (1914) *On Physically Similar Systems; Illustrations of the Use of Dimensional Equations* in: Physical Review 4, H. 4, pp. 345–376. https://doi.org/10.1103/PhysRev.4.345

[15] Damm, J.; Albiez, M. (2023) *Damping Properties of Large-Scale Overlap Joints Bonded with Epoxy Hybrid Resin or Polyurethanes: Experimental Characterisation and Analytical Description* in: Polymers 15, H. 5, pp. 1102. https://doi.org/10.3390/polym15051102