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Efficient strength testing of substructures of agricultural vehicles

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Agricultural vehicles and the implements attached to them are exposed to a wide range of mechanical loads during operation. Ensuring structural durability is of great importance for their reliable operation and the avoidance of unscheduled downtimes. The large number of vehicle configurations, which are adapted to the respective tasks and operating conditions, increases the required complexity of this protection.

Hybrid testing methods facilitate the investigation of different vehicle configurations by reducing the amount of hardware required in the test. In these methods, flexible test bench elements replicate adjacent structures using numerical models. Numerics and experiment are combined in such a way that the numerics determine the component stresses to be reproduced in the experiment and the experimental testing verifies the local strength.

Keywords
Hybrid testing methods, fatigue strength, test simplification, substitute test, integration test

Agricultural machinery and vehicles are subjected to a wide variety of mechanical loads during their operational use in different scenarios. In addition, many agricultural vehicles are multifunctional vehicles, each equipped with different implements and attachments for different tasks. Plows, harrows, mowers, balers, front loaders and field sprayers are just a selection of the attached implements that are used on tractors. Combine harvesters can also be flexibly adapted to different harvesting conditions, e. g. by attaching individual cutting units and other attachments such as swath depositors, straw choppers, grain lifters and cleaning systems. Figure 1 shows an example of a tractor with an attached field sprayer.

Figure 1 : Tractor with attached field sprayer (© Fraunhofer LBF)

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The reliable, durable design of all substructures of agricultural implements and vehicles is a basic prerequisite for the smooth and safe use of machinery and means of transportation. These must be available when the respective work in the field is due and the weather conditions are suitable for this work. A breakdown of important equipment or vehicles, for example during the already labor-intensive harvesting season, can have serious economic consequences and significantly jeopardize the tightly scheduled timetable.

Manufacturers of such agricultural equipment and vehicles therefore pay great attention to ensuring the structural durability of their products (Aramide 2021, Wen 2020, Eckstein 2017, Dimitris 2016, Kumar 2015). They are faced with the challenge that experimental testing for the aforementioned variety of operating conditions and vehicle configurations involves a great deal of effort. Even though numerical simulation tools have led to significant progress in the design and optimization of structures in agricultural equipment in recent decades (Steengaard 2024, Subbaiyan 2021, Wöllner 2021, Dhangar 2017, Verma 2016), experimental proof of strength remains largely indispensable. However, the validity of such a laboratory test is heavily dependent on the selected test boundary conditions, which always represent an abstraction of the actual application. This applies in particular to substructures and systems that are integrated into or attached to elastic structures in a complex manner. These usually involve many internal loads and a pronounced dependence of the load condition on the elastic behavior of the surrounding structure. For vehicle areas whose load and elastic attachment properties differ significantly depending on the vehicle configuration, testing concepts are required that offer a high degree of flexibility to replicate the different boundary conditions. Hybrid testing methods enable faster, meaningful testing of such substructures through simulation-based optimized test designs and offer a high degree of flexibility for variant investigations. These hybrid methods combine numerical and experimental procedures in one testing process. This includes hardware-in-the-loop methods, the use of digital twins of test setups and the simulation-based determination and optimization of variable parameters in the respective test (Landersheim et al. 2022). The latter group of hybrid testing methods also includes the derivation of test designs in which numerical analyses are used to optimize attachment and load boundary conditions for the respective test task. The aim of this optimization is to achieve the simplest possible test setup with the most accurate possible replication of damage for the respective vehicle configuration. Such test approaches are known in the literature from the passenger car sector, for example, but also from the transport vehicle sector (Landersheim and Küppers 2022, Lozia 2022, Landersheim 2016, Soproni 2013, Kiesel 2011, Walter 2007). This article first presents a procedure for optimizing test designs for complexly loaded or complexly integrated substructures and components. Subsequently, possibilities for the implementation of elastic boundary conditions are shown and finally two application examples are presented. The first application example deals with the question of verifying the strength of add-on parts that are subjected to inertial forces and additionally stressed by a structural load path, which is relevant for agricultural vehicles and attachments.

Procedure for the systematic derivation of optimized test designs

A numerical model of the overall system under operating load and a model of the substructure to be tested are required for the optimization of test designs regarding complexity and test validity. Finite element (FE) models are typically used for this purpose. The reference stresses are determined by the model of the overall system under operating load. The test boundary conditions are optimized using a model of the substructure to be tested. Due to the computing time, this optimization is usually not feasible with direct use of the FE models, as the number of parameters would require several thousand simulation runs. The procedure shown in Figure 2 , on the other hand, enables efficient optimization, whereby numerous design variants of the test setup are evaluated.

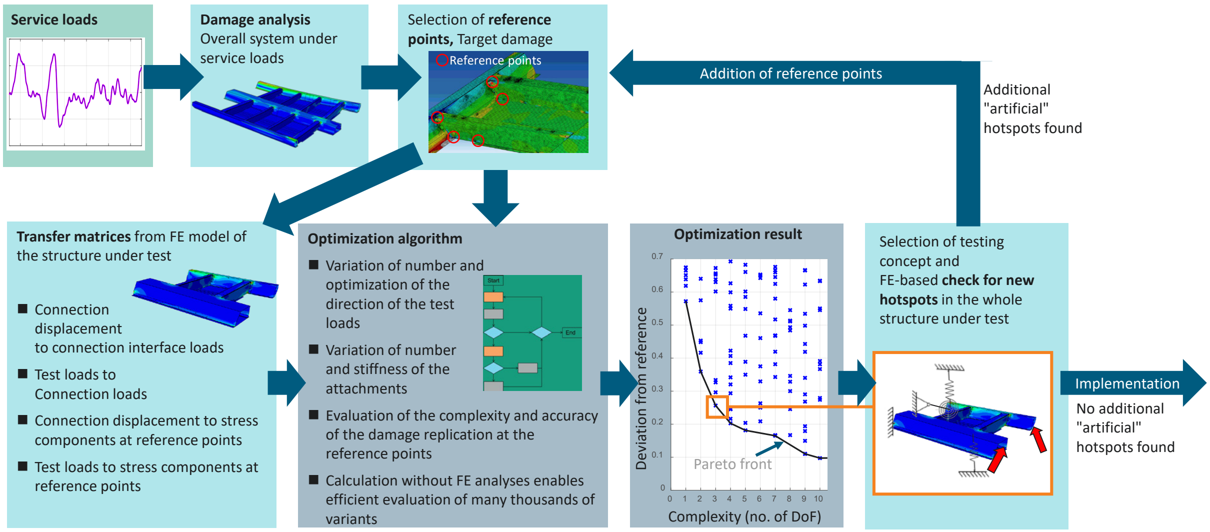

Figure 2 : Procedure for optimizing the substitute test

To do this, possible hotspots must first be identified with the reference model of the overall system and the optimization target positions must be limited to these reference points. The FE model of the structure under test can be used to determine transfer matrices that can be used to compute the time histories of the stress components at the reference points as a function of the external test loads and the elastic boundary conditions. These transfer matrices are determined by calculating quasi-static unit load cases. A unit load case is required for each load that may have to be applied in the test. Here, rigid boundary conditions in the attachment's degrees of freedom need to be applied. If the load direction can only be determined during optimization, a unit load case must be calculated for each possible direction component of the load. Furthermore, a unit load case must be calculated for each degree of freedom of the attachment, in which a unit displacement is specified in this degree of freedom, while all other degrees of freedom of the attachment are constrained by a rigid boundary condition and no external loads are applied. The following transfer matrices result from the reaction forces at the attachment locations and the stress components at the reference points in these unit load cases:

- The stiffness matrix of the structure under test in relation to the degrees of freedom of the attachment,
- The transfer matrix of the test loads to the internal forces (with ideal rigid boundary condition in the attachment's degrees of freedom),
- The transfer matrix from the deformation variables (displacements, rotations) at the attachment's degrees of freedom to the local stress components at the reference points,
- The transfer matrix from the test loads to the local stress components at the reference points.

With these transfer matrices, the effect of each modification in the elastic boundary conditions and the test loads on the local stress at the reference points can be evaluated in just a few seconds.

Depending on the material or the structural element to be evaluated (e.g. bolted joint, spot weld, ...), a suitable method for damage evaluation based on the time history of the stress components must be selected. In the following examples, a critical plane method according to Brown-Miller (Brown 1973) was used in combination with damage accumulation according to elementary Miner (Miner 1945).

The optimization algorithm systematically varies the load application and boundary conditions. The starting point of the optimization is typically a complex reference configuration with many potential test loads and boundary conditions, which originate from an analysis of the load and installation situation in operation. Based on this, the complexity is gradually reduced by selecting and eliminating from all test loads and boundary conditions the one that has the least influence on the stress at the reference points. Based on the reduced configuration, the next simplest solution is found in the same way by evaluating the influence of all remaining test loads or boundary conditions and again eliminating the one with the least influence. This process is continued until the deviation of the load from the reference load becomes unacceptably large. Optionally, a local optimization with a hill-climbing strategy can be carried out downstream, in which load amplitudes and directions or stiffness values are optimized regarding the local stresses. In this case, loads and stiffnesses then deviate quantitatively from the original physical reference configuration.

The optimization algorithm provides the solution with the highest replication accuracy regarding the damage at the reference points for all degrees of complexity examined in the solution space. The degree of complexity results from the number of test loads and the number of elastic boundary conditions used in the test variant. As a result, the optimization delivers a Pareto front of possible solutions, in which each solution offers either a lower complexity or a higher accuracy compared to any other solution in the Pareto front. The solution that represents the best compromise regarding the respective test objectives is then selected from these solutions. Since the optimization is only carried out regarding the selected reference points, the entire structure under test must be evaluated with the selected solution in order to rule out the possibility that the planned simplifications lead to new, "artificial" hotspots that would only occur due to the simplification of the test setup. If such artificial hotspots are found, these points must be considered as additional reference points in the optimization and the optimization must be repeated including them. If no artificial hotspots are found in this check, the optimized test concept may be selected for realization.

Tools for replicating structural stiffness

The loads optimized for testing are usually applied using hydraulic or electric servo actuators. The elastic boundary conditions, which replicate the elasticity of the adjacent structure, can be realized using mounts with specifically optimized stiffness properties that are individually manufactured for a specific test. Such a solution enables the realization of complex elastic boundary conditions in which, for example, stiffness values in several degrees of freedom must be replicated at an attachment point and, if necessary, couplings between degrees of freedom must also be taken into account. However, these parts usually have to be redesigned and manufactured for each test, even if only the use in a different variant of the structural environment is to be investigated. An example of such a solution is shown in Figure 3 on the left.

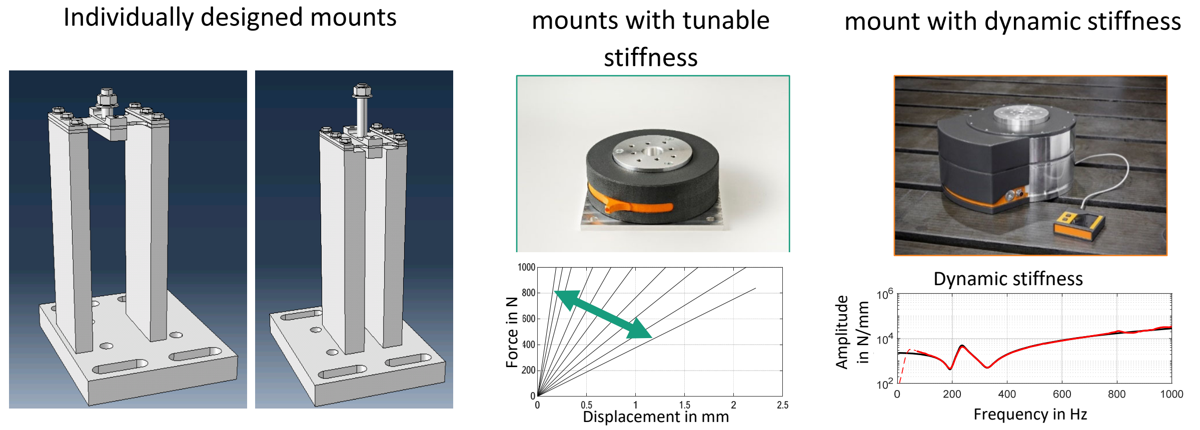

Figure 3 : Several options for simulating attachment stiffnesses. From the left: Individually designed mounts, mounts with tunable stiffness (Millitzer 2021, Hansmann 2018), mounts with dynamic stiffness (Millitzer 2021)

By using the simplest possible geometries for this purpose, the cost of manufacturing parts is minimized. Without the individual manufacturing of parts, the attachment stiffness can be replicated with the mounts with tunable stiffness implemented prototypically at Fraunhofer LBF, which are shown in the middle of Figure 3 (Millitzer 2021, Hansmann 2018). Their stiffness can be tuned to the desired test boundary conditions by adjusting a slider. These tunable mounts thus enable fast and cost-effective variant tests and are themselves designed to be durable so that they can be reused for other tests even after a test has been completed. The stiffness of mounts with tunable stiffness can only be adjusted in one translational degree of freedom, but several of these mounts can be combined at one attachment location, allowing stiffness properties to be replicating in several degrees of freedom, including rotational ones. If, in addition to the static stiffness, dynamic structural properties are also to be replicated, this can be done with a version extended by an active component, which was also prototypically implemented at Fraunhofer LBF and can be seen in Figure 3 on the right. In addition to passive stiffness, this contains an electric actuator that can be coupled with models of oscillatory structures via a hardware-in-the-loop interface and thus replicate their behavior (Millitzer 2021).

Application examples for simplified testing methods using optimized test designs

In this section, a battery attachment for a commercial vehicle and a structurally integrated high-voltage storage housing are used as examples to illustrate how the previously described procedure for the systematic derivation of optimized test designs enables simplified testing of components and structures.

The first application example involves the development of a simplified test bench for the attachment areas of a battery that is attached to the side of the frame of a commercial vehicle (Figure 4).

Figure 4 : Battery box attached to the frame of a 12t-class light truck (© MAN)

Loads resulting from inertial forces acting on the attached part occur in these attachment areas. In addition, the frame deformation is of significant importance for the stress on the attachment area, especially for attachments that are connected to the frame at several points. There are 35 load application points on the frame of the commercial vehicle considered in this example, which are shown in Figure 5 . Three non-proportional translational forces act at each of these points, resulting in a total of 105 non-proportional loads.

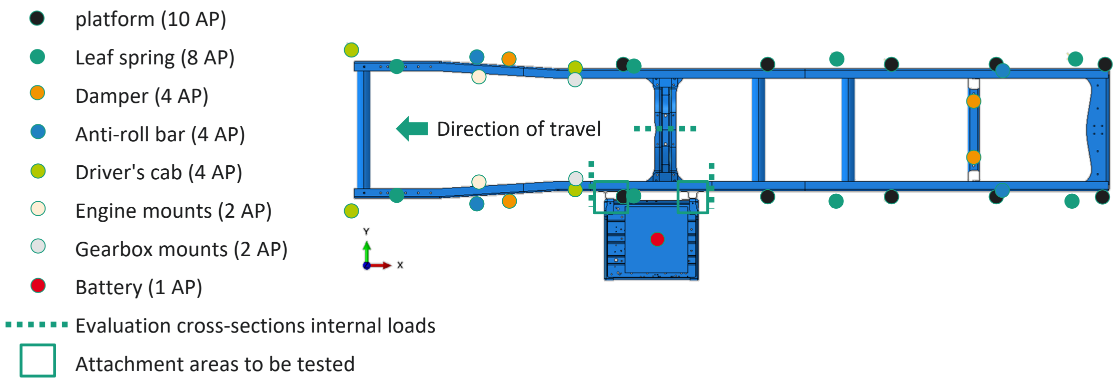

Figure 5 : Load application points in the frame of the commercial vehicle (AP: attachment location) (Landersheim and Küppers 2022)

The load on the frame section to which the commercial vehicle battery is connected can be fully mapped with 27 non-proportional loads. These are the 18 internal forces on the longitudinal and cross members, one triaxial load introduction each on the attachment points of the platform and of a leaf spring in this area, as well as the inertia loads of the battery itself. These 27 loads form the reference configuration for the optimization of the test design according to the procedure shown in Figure 2. The result of the optimization is a simplified test concept that generates a damage-equivalent load with only three equivalent loads. Uniaxial forces are applied by hydraulic actuators at the front end of the longitudinal member, at the platform attachment point and at the battery's center of gravity. The load introduction at the leaf spring attachment point is omitted, as it can be combined with the load introduction at the platform attachment point due to the spatial proximity. The internal forces at the rear end of the longitudinal member and on the cross member are generated by the rear clamping of the longitudinal members. The clamping itself is assumed to be ideally rigid, but the clamping length of the two longitudinal members has a significant influence on the attachment stiffness of the battery rsp. the cross member and thus on the force flow and the local damage (Figure 6).

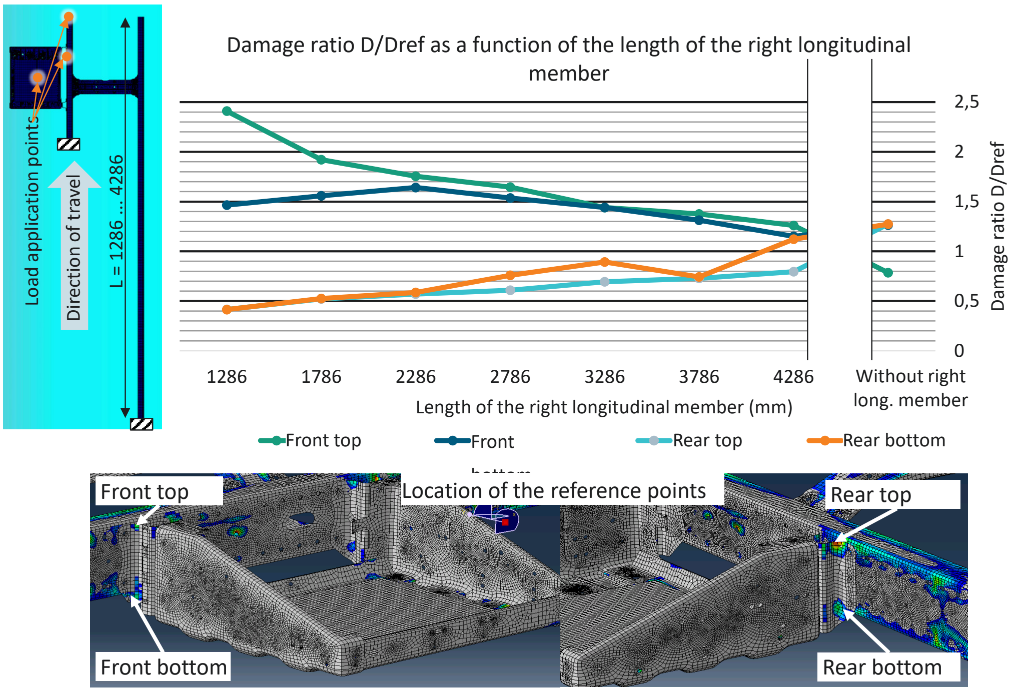

Figure 6 : Relationship between the damage at four reference points at the battery attachment and the clamping length of the opposite longitudinal member in relation to the reference damage (Landersheim and Küppers 2022)

Here, the length of the right longitudinal member was varied in the test section. For each selected beam length, the load vectors at the three load application points were optimized regarding damage-equivalent stresses at four reference points, two at the front and two at the rear attachment, at each atachment one at the top and one at the bottom. The rear end of the longitudinal beams is rigidly clamped, the front end is free. Figure 6 shows that the deviation of the damage decreases with increasing length of the right longitudinal member - which corresponds to a decreasing right-sided attachment stiffness of the cross member. By varying the length alone, the maximum deviation of the damage at the reference points can be reduced from a factor of 2.4 to a factor of 1.3. With the inclination of the S-N curve of k = 5 assumed here, this corresponds to a reduction of the deviation in the damage-equivalent stress amplitude from 20 to 5%. If the right longitudinal member is omitted completely - which corresponds to a right-sided attachment stiffness of the cross member of zero – this also results in a maximum deviation of the damage by a factor of 1.3, so that a test with a small structure under test can be realized here. The optimized design of the simplified testing concept is shown in Figure 7.

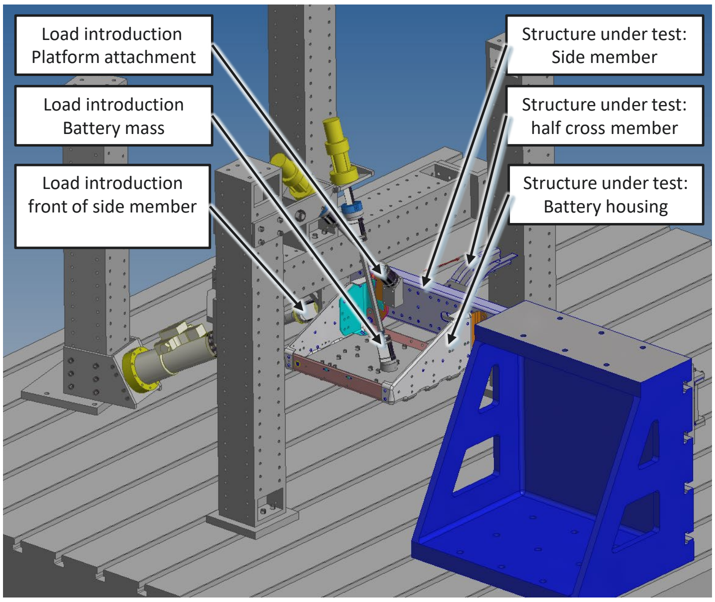

Figure 7 : Simplified replacement test designed for testing the battery attachment (Landersheim and Küppers 2022)

The integration of numerical analyses in the sense of hybrid testing thus enables a largely damage-equivalent but significantly simplified substitute test for this substructure. Despite the complex load situation of the substructure with a total of 27 load components, the damage at the four selected evaluation points can be replicated with just three actuators. The algorithmic procedure shown in Figure 2 enables efficient automation of the design process by limiting the evaluation to previously selected reference points and utilizing the linearity of the FE models by reducing them to transfer matrices. This enables targeted optimization, as a large number of different variants can be investigated in a short period of time. The substitute tests derived in this way offer considerable potential for validating and optimizing substructures more efficiently due to lower costs (number of actuators, space requirements, energy consumption) and earlier availability, taking better account of the increasing number of variants and thus accelerating the overall product development process.

Hybrid testing methods are also interesting for segments of larger complex structures (Landersheim et al. 2022). Figure 8 shows a test setup for a support structure segment of a structurally integrated high-voltage storage system. In the application example, various innovative joining processes developed in the “Light Materials for Mobility (LM4M)” project at Fraunhofer are tested realistically on this segment. The tunable stiffness elements prototyped at Fraunhofer LBF are used in this test rig (Figure 3, center). These can be used to replicate different stiffnesses of the surrounding car body structure and specifically adjust the stress states in the area of the joints, as shown in Figure 8 using the example of a strain measurement point (strain gauge 6).

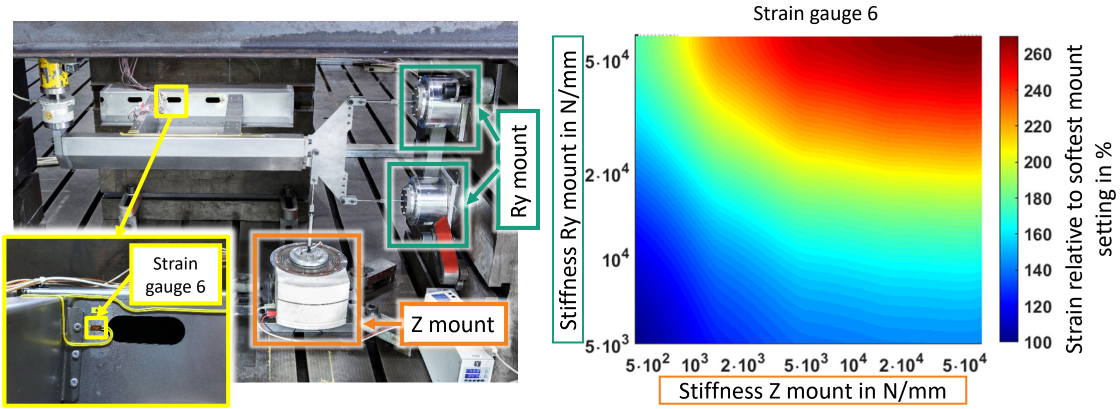

Figure 8 : Simplified equivalent test for a support structure of a structurally integrated high-voltage storage system (left) and dependence of the local strain on a selected strain gauge on the stiffness of the tunable mounts (Z and Ry mounts) in this test setup (right) (Landersheim et al. 2022)

Three tunable mounts at the rear end of the side sill are used to replicate the stiffness of the structure not contained in the structure under test in the vertical direction (Z mount) and in the longitudinal direction (Ry mount), whereby the distance between the two Ry mounts results in a rotational stiffness around the transverse axis. The strain at the strain measuring points can be significantly influenced by specifically adjusting the stiffness of the mounts. In Figure 8 on the right is shown that within the adjustment range of the mounts, an increase in the strain amplitude at the selected measuring location (strain gauge 6) can be achieved by a factor of 2.7. This makes it possible to test different installation situations of the structure with one test rig by changing the mount properties, which correspond to different vehicles or vehicle variants and configurations. The target properties or target strains to be replicated are determined by numerical analyses of the overall structure in the sense of a hybrid testing method.

Conclusions

Hybrid testing methods are an important tool for the validation and optimization of fatigue strength in an efficient product development process. They can be used to test substructures and components that are characterized by significant interactions with adjacent structures individually and at an early stage in the development process under the real stresses to which they are also subjected in the overall system. This avoids lengthy and expensive modifications due to weak points that are only discovered at a late stage. This enables earlier lightweight construction optimization as well as more extensive variant testing and component characterization than is possible when testing in the overall system. This offers great potential for increasing efficiency in fatigue strength testing, particularly for the wide variety of vehicle configurations and load scenarios in agriculture. Such an approach combines the advantages of numerical and experimental methods in the testing process. Today, numerical simulation is capable of deriving the external loads and internal stresses of the structures with sufficient accuracy and transferring them realistically to simplified tests using the methods described. However, the actual component-specific material strength can still only be determined with sufficient certainty in experiments. By using simplified, but nevertheless meaningful components and substructure tests, this can be done to a greater extent in earlier product development phases. The number of tests required in overall vehicle testing can be reduced through better validation of the individual structures and, at best, limited to the series release.

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Notes

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