A SEMI-ANALYTICAL APPROACH TO IDENTIFY SOLUTION SPACES FOR CRASHWORTHINESS IN VEHICLE ARCHITECTURES

Lailong Song
Johannes Fender
BMW Group, Research and Innovation Center
Germany

Fabian Duddeck
Technische Universität München
Germany

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ABSTRACT

In an early design phase for vehicle crashworthiness, the use of classical optimization is limited. One reason for this is that development of structural components is distributed over different departments. Additionally, crash performance depends on several components and their interaction. Common components in vehicle architectures are subject to various load cases in multiple vehicles. Thus, the entire vehicle architecture has to be considered during optimization. In order to enable distributed development the system needs to be decoupled, which means that a variation in one component does not require modifications of other components in order to reach the global structural performance goal.
The objective of this paper is to introduce a method to define the component-wise force-deformation requirements of vehicle architectures for front crash structure design. The force-deformation properties of the components are subject to constraints, from which an analytical description of the design space of the vehicle architecture is derived. The optimal orthogonal solution space within this design space is identified via optimization process. This results in maximal intervals for variations of the component forces over their deformations under the given boundary conditions. The validity of the solution space is proven through explicit FE simulation.

INTRODUCTION

1.1 Load Case (USNCAP)

In 1978, the U.S. National Highway Traffic Safety Administration (NHTSA) introduced the crash test to evaluate the crashworthiness of the vehicles on market. This result is published in the U.S. New Car Assessment Program (USNCAP). One of the test scenarios is a vehicle impact against a fixed rigid barrier with 56km/h. Two dummies, which are protected by the restrain system, are seated in the front seats. The injury criteria are assessed based on the data collected during the crash by the dummies.
In vehicle crashworthiness design, the system is decomposed into two main sub-systems: vehicle structure system and restraint system. The analyse on the vehicle structure response, which is fundamental to the occupant protection, is the primary focus in this paper.

1.2 Structure Design

The crash relevant components are designed to absorb the kinetic energy of the vehicle by plastic deformation. These components usually form several parallel load paths going through the front structure of the vehicle in driving direction. During the deformation of the load paths, the **acceleration at the B-pillar** must not exceed the critical value. The B-pillar acceleration is correlated with the dummy acceleration, which is restricted by the injury criteria (Huang, 2002). Furthermore, the compartment deformation is constrained to prevent the occupants from crushing and penetration injury. The **firewall intrusion** is considered as a measurement of the severity of the compartment deformation in front crash. In addition to the dummy protection, the **number of the affected components** depending on the crash velocity is considered due to the structural reparability and reusability.

1.3 The Vehicle Cluster within Architecture

For economical reasons, the vehicle are desired to share as many components as possible. The vehicles are grouped into one cluster if they are coupled in the following ways:

Direct coupling: When several vehicles share common components, they are directly coupled. (shown in Figure 1)

Indirect coupling: The indirect coupling denotes the situation, in which several vehicles don't have common components. Nevertheless they have common components with the same vehicle(s) as shown in Figure 1.

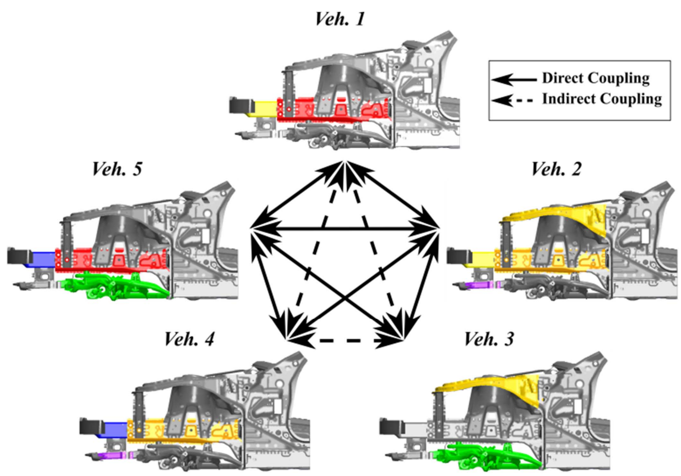


Figure 1. The coupling relation of a cluster with five vehicles.

The common components, which are assembled in different vehicles, must fulfill the functional requirements of each vehicle respectively. The design of common components is difficult if the mass distribution and feasible deformable lengths of the vehicles vary. Therefore, an approach to coordinate the local requirements from all the individual vehicle structures into one requirement for the component design should be established. These requirements defined in early phase can guide the later component design.

1.4 Simplified Modeling

The simplified model can be used to derive the functional requirement of the original structure effectively in the whole vehicle design process.
One prominent approach to simplify the structure is the lumped mass-spring (LMS) model. It was introduced by Kamal in the early 1970s. The frontal structure of the vehicle is represented one-dimensionally by masses and springs. This model delivers acceptable results seeing that the main features of the structure behavior in the crash are captured (Kamal, 1970). However, the characteristics of the springs must be collected from experiment, which limits the applicable field of the approach. Based on this, Ni and Song built a new model, in which the springs are substituted by shell and beam. This frame structure is analyzed by the finite element simulation to identify its behavior in the crash, based on which a study is conducted to define appropriate force-deformation curves for all the components (Ni & Song, 1986). Lust established a two-phase approach to study the connection between component property and the response of the overall vehicle structure in crash. In the first phase, the force-deformation curve of the component is individually analyzed. The identified force-deformation curve is considered to be scalable regarding the wall thickness of the component. In the second phase, the mass-spring model is built to obtain the overall structural response (Lust, 1992). Due to the increasing demand on the accuracy of the simplified model in prediction, the deviation between static crush test and real dynamic crash load case was put into consideration. Kim developed a mass-spring model for a quasi-static load case (Kim, Mijar, & Arora, 2001).
For the simplified model stated above, if the force-deformation curves of the component are calibrated to achieve the overall structural performance goal in crash, in the further component design process, optimizing the component to match the predefined force-deformation curve is not plausible. On this account, the concept of solution space was

developed by Zimmermann (Zimmermann & von Hoessle, 2013). The simplified model provides intervals for the force-deformation curves. The intervals calculated for all the components form the solution space of component design. This solution space is applied during component design: if the force-deformation curve of the component lies inside the solution space, the entire structure fulfills the expected functional goal. The solution space is identified with two approaches: the stochastic approach requires an FE model for the calibration of a load path model, which has its limitations in the early phase (Zimmermann & von Hoessle, 2013); the analytical approach includes a two-level solution procedure which sometimes over constrains the solution space. When calculating the solution space for vehicle architecture with common components in different vehicles, the analytical approach confronts an over determined system and thus delivers no solution space (Fender J. , 2013).

1.5 Vehicle Architectures

In order to minimize the development cost of the vehicle, the concept of the vehicle platform is introduced. A platform denotes a technical basis, on which various vehicle models can be constructed. The platform is also called vehicle architecture. In practice, besides the economical reason, the producers can take more advantage of the concept, e.g. less variant in components, efficient innovation, stronger global standardization and diversity in product (Gonçalves & Ferreira, 2005).
The common parts that make up an automotive platform are: chassis, suspension, steering mechanism and drive train components (WhyHighEnd.com, 2010). Analogously the platform concept is also applied for the corresponding components in Crash. The vehicles, which share the common components in the passive safety design, are grouped in one cluster. The solution spaces for the different vehicles with common components are identified by the stochastic approach based on a simplified load path model. The common components obtain a single functional requirement which fulfills the structural goal in different vehicles respectively.

ANALYTICAL SOLUTION SPACE

2.1 Analytical Solution Space for Single Vehicle

2.1.1 Basic Concepts The process of the vehicle structure design is divided into several phases. The V-model shown in Figure 1 illustrates the detailed division of the phases. In the early phase, the package and platform of the new vehicle are decided. Thereby the rough mass distribution and topology are available. The structural parameters are thus extracted.

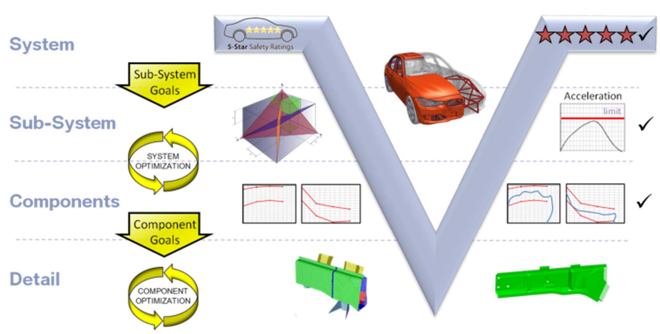


Figure 2. The process of structure crashworthiness design. **(Fender J. , 2013)**

Available deformation length: The available deformation of the front structure is the primary factor for the energy absorption. The total deformation length can be derived from the length of the frontal structure, the drive type, predefined topology and the firewall intrusion. This information is available and used for crashworthiness design in the early phase.

Mass: In the USNCAP front crash test, the impact velocity is predefined. Hence the mass of the vehicle determines the kinetic energy of the system to be dissipated. For the design of frontal structures, the total mass is divided into two parts. The mass of the rear part of vehicle is concentrated at one point behind the firewall. The mass of the front end is distributed over the structure. Each component is attached with a concentrated mass, this simplification is proved to maintain the sufficient accuracy (Fender, Duddeck, & Zimmermann, 2014).

The geometry space and deformation space: The vehicle structure can be modeled using surrogate elements and concentrated mass points. In the symmetric front-crash, since the dominant momentum change happens in the driving direction (x direct), only the resistance forces in this direction are taken into consideration. The deformation conjugated to the force regarding energy is thus the deformation in x-direction. The maximal deformable length of the component is estimated in the early design phase. When integrated into the structure, the components are blocked often by rigid devices in between. In order to predict the actual available deformation of each component, a geometry space is first built up. The deformation space, which is significant for kinetics and energy absorption, is constructed by trimming the geometry space. Sections are inserted where a mass point or an ending of the component are met. The shortest load path is the bottle neck of the feasible deformation of the structure as shown in Figure 3.

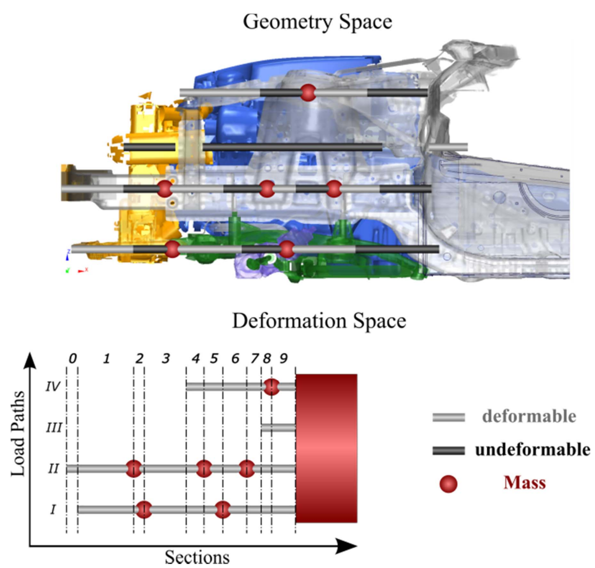


Figure 3. Geometry space vs. deformation space.

<u>2.1.2 Constraints</u> As discussed in section 1.2, three criteria are defined, in order to describe the performance of the structure in crash. In this section, the functional constraints are discussed based on information included in the deformation space.

Critical acceleration: The acceleration of the vehicle compartment is evaluated section wise in the deformation space. Therefore, the critical acceleration gives out the critera on the force levels in components:

$$a_i = \frac{F_i}{M_{act,i}} \leq a_{crt.i} \tag{1.}$$

In which F_i is the sum of the axial resistant forces of all parallel load paths in section i. $M_{act,i}$ is the sum of the masses whose velocities are bigger than zero. This results in a system with N inequalities. N is the number of the sections of the system. If the acceleration in each section is smaller than the critical value, the structure fulfills the acceleration criterion.

Firewall intrusion: The criterion on the maximal firewall intrusion is satisfied if the velocities of all the mass point are null, before the feasible deformation is totally used up. In the deformation space, this condition can be described thusly:

In section i:

$$\int F_i(u)du \geq \frac{1}{2}M_{act,i}v_i^2 - \frac{1}{2}M_{act,i}v_{i+1}^2 \quad (2).$$

In which,
$F_i(u)$: is the sum of the axial force from all the components in section i over u
u : is the deformed length of section i
$M_{act,i}$: is the active mass of section i
v_i: is the velocity of the structure when the section i starts to deform
The final velocity of the previous section and the initial velocity of the subsequent section are the same. And the velocity of the compartment should be zero after the last section in front structure deforms. In consequence, when the inequalities are summed up section wise, the terms with the intermediate velocities are eliminated, which yields the inequality:

$$\sum_{i=0}^{N} \frac{\int F_i(u)du}{M_{act,i}} \geq \frac{v_0^2}{2} \quad (3).$$

If Eq. (3) is fulfilled, the firewall intrusion is restricted.

The order of deformation: If the impact velocity is relatively low, it is not necessary to absorb energy by collapsing all the components. Moreover, the successive deformation behavior mitigates the dependencies of the components. On this account, the order of deformation criterion requires that:

$$F_1(u_1) - M_1 a(u_1) \leq F_2(u_2 = 0) \quad (4).$$

The indices represent the component 2 locates after component 1 in the same load path.
Up to here, the three constraints for the force-deformation curve of each component are introduced based on the information in deformation space.

2.1.3 The Concept of Solution Space One of the basic goals for the passive safety design in the early phase is to set up the expected force-deformation characteristic for the components. However this goal is ambitious because of the limited available information.
Zimmermann established an approach to find out a robust, compatible and flexible guideline for the component design. The fundamental concept can be explained in an example with a primitive deformation space, shown in Figure 4. The three boundary conditions are applied onto the axial resistance force of the components. The feasible field of designs is the triangle, in which the optimal design A is located. The optimum offers not only the lowest acceleration but fulfills the firewall intrusion and order of deformation constraints as well. However, this design is neither robust nor independent, i.e. If F_1 is changed, the design may violate the constraints. F_2 must be adjusted correspondingly to bring the design back to the feasible field.
The solution space approach creates in this situation a suitable rectangle (a hypercube in high dimensional space) inside the design space. All the designs inside this solution space fulfill the three constraints. In each dimension, the level of the resistance forces is restricted by an interval. For a component with several sections, the intervals form a corridor for the force-deformation curve of the component.
Inside the solution space, the change of the resistance force level in one dimension doesn't lead to constraint violations in other dimensions, which means that the change of force level in one component doesn't require the adaption of the others to fulfill the overall structural requirments.
With the solution space concept, the passive safety design in early phase can be transformed into the problem: calculate the solution space of the structure; i.e. identify the corridors for the force-deformation curves of the components. In the component design phase, if the force-deformation curve of individual component locates inside the corridor, the total structure fulfills the three constraints.

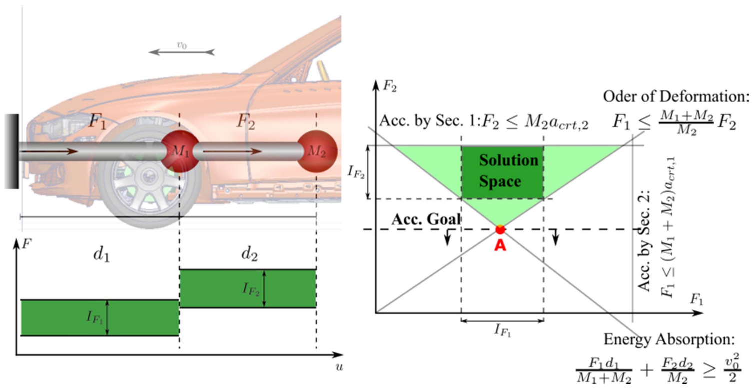


Figure 4. Solution space of a structure with two components. **(Zimmermann & von Hoessle, 2013)**

2.2 Solution Space for One Cluster within Vehicle Architecture

If the components have identical length and concentrated mass in the geometry space, these components can in principle be defined as common components. However, the commonality is in reality based on more criteria from other disciplines. Therefore, the common components are manually pre-defined.

2.2.1 Construction of the Coupled Deformation Spaces The common components are marked with the same name in the deformation space. The relationships are managed using a mapping. The structure of the mapping is shown in Figure 5.

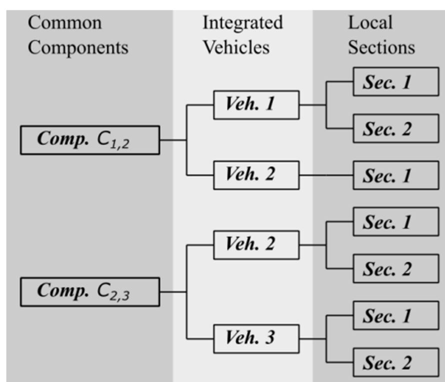


Figure 5. Mapping list of the vehicle relationship in cluster.

The force-deformation curve of the component is discretized by sections. As a consequence, the common components, which share the same corridor, must have the same section discretization. In another words, the section division of common components should have identical distances and count. For this reason, the artificial sections are inserted into the deformation spaces to synchronize the section division of the common components. For instance, three deformation spaces with common components are synchronized in the following way:

a. Independent construction of the deformation space

As shown in Figure 6 in step I, the three deformation spaces are built independently for each structure. The building process is the same as for single structure – sections are inserted where a mass point or an ending of the component are met.

b. Consecutive synchronization of sections for each component

The new artificial sections are inserted, so that the common components have the identical section division as shown in Figure 6 in step II and III. Since the sections are transversely through all parallel load paths, the parallel components are affected as well. This synchronization leads to a finer discretization for the deformation space. When the common components have comparable relative spatial positions among structures, the section count for the common components converges. Important positions (mass point and ending of component) within the spatial range of the common components are eventually marked with section bounds. In the case of a cluster with N

vehicles, each has p_i components and q_i mass points, the synchronization converges before maximal $\sum_{i=0}^{N}(p_i + q_i)$ iterations.

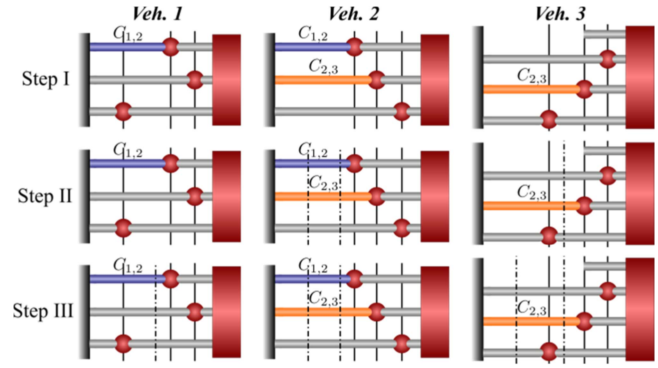


Figure 6. Artificial sections are inserted to synchronize the deformation spaces.

2.3 Solution Space Identification

The goal of this solution process is to find the largest possible solution space in the design space, which is described by the three constraints. The notations used in the solution process are the following:
$F_{u(pper),ij}/F_{l(ower),ij}$: the upper and lower boundaries of the force interval in section i, load path j.
M_{ij} : the value of the mass point at section i, on load path j.
$M_{act,i}$: the active mass when the system deforms till section i.
d_i : the length of the section i.
$a_{crt,i}$: the critical acceleration of the section i.
v_0 : the initial velocity of the vehicle

2.3.1 Constraints The upper and lower boundaries of the intervals are the unknowns to be identified in the solution process. Suppose that the system has N sections and M load paths. The constraints for an optimization problem can be formulated as follows:
The upper boundaries of force-deformation curves in each component should satisfy the inequalities for critical acceleration:

$$\sum_{j=1}^{M} F_{u,ij} \leq M_{act,i} \cdot a_{act,i} \tag{5}$$

The lower boundaries of force-deformation curves in each component should satisfy the equalities Eq. (6) w.r.t. the energy absorption criterion:

$$\sum_{i=1}^{N} \left(\sum_{j=1}^{M} F_{l,ij} \right) \frac{d_i}{M_{act,i}} = \frac{v_0^2}{2} \tag{6}$$

The order of deformation between components in the same load path applies constraints between the upper and lower boundaries of the intervals. If a component ends at section i, the constraint is:

$$F_{u,ij} - \frac{M_{ij}}{M_{act,i}} \sum_{j=1}^{M} F_{u,ij} \leq F_{l,(i+1)j} \tag{7}$$

These constraints are applied to the intervals of the force-deformation curves for each vehicle structure in the cluster. Among the vehicles, extra equalities are needed to ensure the identical corridors for common components. For instance, components C_A and C_B are common in deformation spaces D_A and D_B, which are built from the structure of vehicle A and B respectively. $F_{u,ij}^{A}$, $F_{l,ij}^{A}$ are the upper and lower boundaries of the force intervals for C_A in D_A with the section set I_A while $F_{u,mn}^{B}$, $F_{l,mn}^{B}$ are the boundries of the force interval for C_B in D_B with the section set M_B. The section set I_A and M_B have an offset δ, i.e. $I_A = M_B + \delta$. The commonality requires that:

$$F_{u,ij}^{A} \equiv F_{u,(i+\delta)n}^{B} \ , F_{l,ij}^{A} \equiv F_{l,(i+\delta)n}^{B} \quad \forall i \in I_A \cap \{M_B + \delta\} \tag{8}$$

2.3.2 Objective Functions Under these constraints, the optimal values of the upper and lower boundaries are calculated by quadratic programming. The objective function is defined as follows:

Width of the corridor: In the application, it is more flexible to design the component with wider corridor for the force-deformation curve. Thus, the largest solution space is desired within the design space. The closer the corridor boundaries approach to the constraints, the wider the corridors are. In order to maintain the convexity of the optimization problem, the objective function is formulated with sum of squares (SoS).
The widths of the corridor for different components are controlled by a weighting factor. This is practical, when the force-deformation behavior of one component is easier to control (e.g. crushing component) than that of another component (e.g. buckling component). Thus, the widest corridor is achieved by finding the minimum of Eq. (9).

$$\text{min.} \quad \Psi = \sum_{i=0}^{N} \left[\left(\sum_{j=0}^{M} \omega_{ij} \right) \left(\sum_{j=0}^{M} F_{u,ij} - M_{act,i} \cdot a_{crt,i} \right)^2 \right] \qquad (9).$$

In which ω_{ij} denotes the weighting factor of the corridor segment at section i and load path j .

Smoothness of the corridor: If dramatic overshootings exist in the corridor, it is difficult to design the force-deformation curve of the component to fulfill the corridor. Therefore, the smoothness of the corridor should be tuned to reduce the complexity of the engineering work. For component C_k with S corridor segments, the objective function for corridor smoothness is written as:

$$\text{min.} \quad \phi_k = \frac{1}{S-1} \sum_{i=1}^{S} \left(F_{m,ij} - \bar{F}_M \right)^2 \qquad (10).$$

In which $\bar{F}_M = \frac{1}{S} \sum_{i=1}^{S} \left(F_{u,ij} + F_{l,ij} \right)/2$. Φ is the sum over the objective functions of each corridor.

Uniform distribution of the corridor widths: The force-deformation curve to be designed may not fulfill an extreme narrow corridor. Therefore, the widths of the corridors should be be as uniform as possible. If the influence of the pre-defined weighting factors is eliminated, the objective function is formulated to minimize the variation of the corridor widths:

$$\text{min.} \quad \Theta = \frac{1}{D-1} \sum_{i=1}^{N} \sum_{j=1}^{M} \left(\frac{F_{u,ij} - F_{l,ij}}{\omega_{ij}} - \overline{\Delta F} \right)^2 \qquad (11).$$

In which $\overline{\Delta F} = \frac{1}{D} \sum_{i=1}^{N} \sum_{j=1}^{M} \left(F_{u,ij} - F_{l,ij} \right)/\omega_{ij}$, and D is the number of corridor segments.
As a concequence, the solution process is transferred into a multi-objective optimization problem. The overall objective function is built by weighted sum of the sub-objective functions Eq. (9-11):

$$\text{min.} \quad \Sigma = \Omega_{\mathrm{w(idth)}} \cdot \Psi + \Omega_{s(moothness)} \cdot \Phi + \Omega_{d(istribution)} \cdot \Theta \qquad (12).$$

The objective function is formed by SoS and therefore semi-positive definit.The equality and inequality constraints are linear. As a result, a unique optimum of this convex problem can be found by interior point method (IPM) (Nocedal & Wright, 2006) (Vandenberghe, 2010).

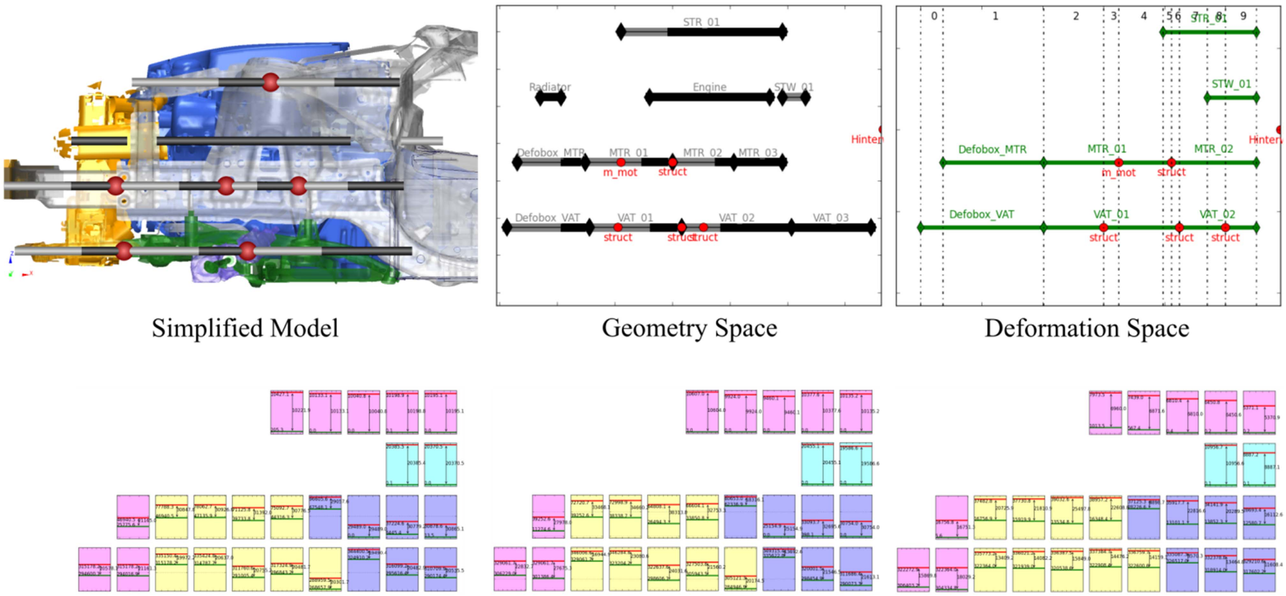
RESULTS

3.1 Solution Space Calculation

The upper and lower boundaries of the force interval in each section and load path are packed into the solution vector $\vec{x} = [F_{l,ij}, F_{u,ij}]^T, i \in [0, N], j \in [0, M]$. This solution vector is obtained by solving the quadratic optimization problem:

$$\min. \quad \vec{x}^T H \vec{x} + b^T \vec{x} \tag{13}$$

under the equality and inequality constraints. In which H is the Hessian matrix of Σ and b is the first derivative of Σ. Tuning the weighting factor of the sub-objective functions leads to different optimal solution spaces as shown in Figure 7.



Simplified Model Geometry Space Deformation Space

Opt. Balanced Distribution Opt. Width Opt. Smoothness

Figure 7. Calculation of the solution space concerning different applications.

A solution of the cluster is shown in Figure 8, which shows that the common components (marked with red and green respectively) integrated in different vehicles are constrained with the identical corridors. For each vehicle, the deformation spaces before and after synchronization are shown on the left in Figure 8.

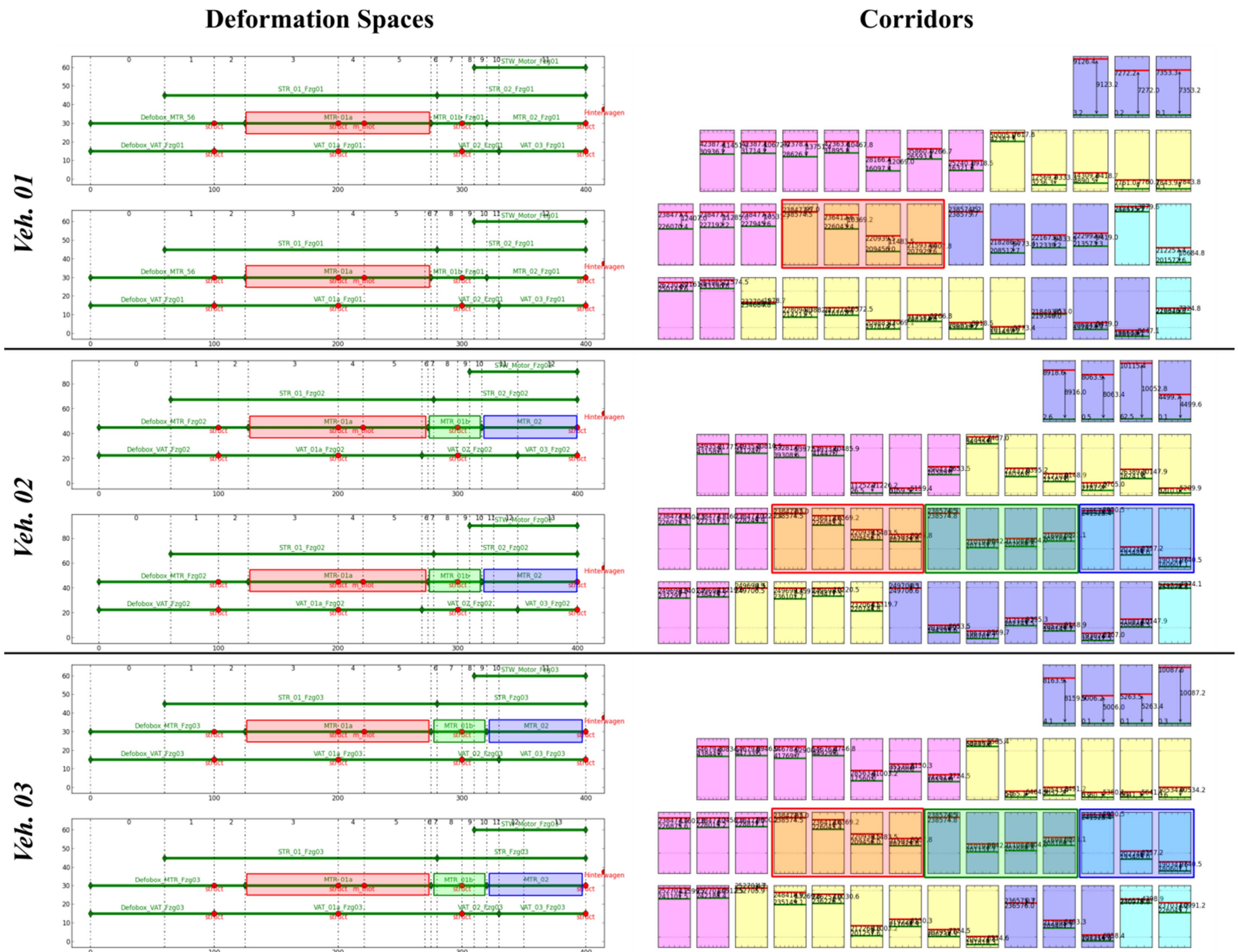


Figure 8. Corridor calculation for vehicle cluster.

3.2 Validations of the Component Functional Goals

In order to validate the method, a simplified FE model is constructed. The structure with four thin-wall components is crashed against a rigid barrier. The acceleration of the mass at the back of the structure is constrained. The solution space of the structure is calculated with the method stated above. In the initial design, the force-deformation curve of the last component violates its corridor; the acceleration of the mass exceeds the critical value as shown in Figure 9. In order to fulfill the goal of structural design, the component is modified (e.g. variation in wall thickness, introduction of beads and holes) to yield a force-deformation response which lies inside its corridor. The acceleration goal is subsequently achieved as shown in Figure 9.

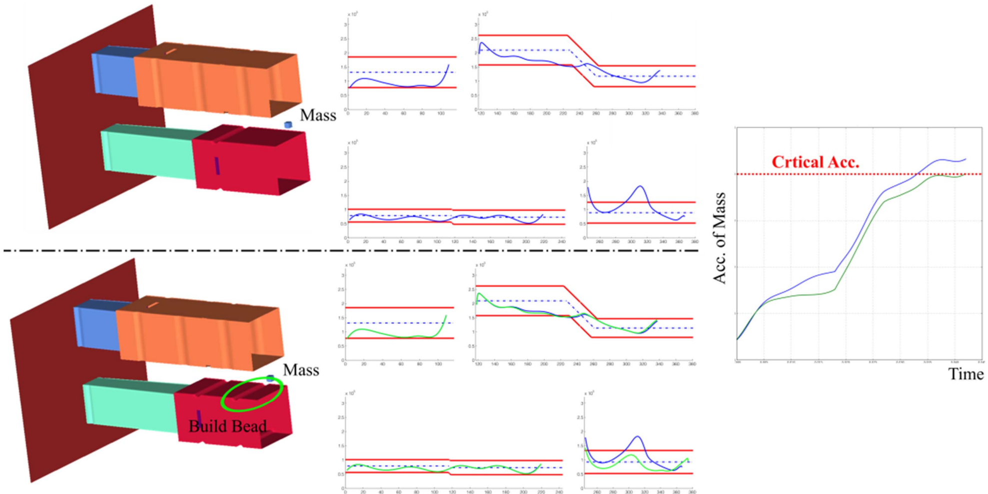


Figure 9. Component design based on corridors.

CONCLUSIONS

The solution space of the vehicle cluster is described analytically and identified through the numerical optimization. The approach can be used to decouple the design of the components while maintaining the commonality of the vehicle architecture. This solution space provides each component an interval for force-deformation responses. These intervals as the functional goals, compared with a single curve, ensure more flexibility for the component design.
With the solution process established in this work, the features of the solution space can be adjusted by tuning the weighting factors in Eq. (12) in order to minimize the effort of the structural optimization in component design.
As a conclusion, this approach can serve the V-model design process by establishing the functional goals for individual components within vehicle architecture.

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