NUMERICAL INVESTIGATION AND IMPROVEMENT OF THE CRASH BEHAVIOUR OF A SMALL AIRCRAFT COMPOSITE STRUCTURE

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Abstract

The ambition of the “Safety-Box” project is to increase occupant safety of an aircraft according to the EASA CS-23 guidelines. To investigate and improve the crash behaviour of a composite aircraft structure a representative impact scenario has been determined. These fixed conditions have been applied in the simulation model and will also be considered when testing the impact of a typical small four seated aircraft. Therefore the whole aircraft structure, with its actual composite lay-up and main attachment parts, was modelled and simulated using the explicit FE code Abaqus. The crash simulation of the baseline structure gave a first impression of the structural failure modes at critical regions, which had to be improved. To provide a better energy absorption capability, crash elements had to be integrated into the aircraft fuselage structure. Aluminium honeycomb sandwich cores and CFRP crash tubes had been identified as suitable energy absorbing components and characterised by component testing concerning their crushing behaviour. Crash elements had been implemented into the FE model using data gained from these qualifications and their positions and properties were optimised in several iterative calculations. An experimental test set-up consisting of auto cranes, which were used to create a pendulum swing, was planned to validate the prior simulations and improvements.

1. Introduction

Due to their high potential to create efficient and well performing light weight structures fibre reinforced plastics are a good material to produce small aircraft for the General Aviation market. The

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particularly advantageous properties of these composite structures turn into negative aspects considering crashing behaviour. In case of a plane crash the stiff and strong materials encourage a hard impact, which could affect the occupant safety. Metal based aircraft constructions provide better energy absorption thanks to the ductile failure behaviour of aluminium. To reduce the high risk of serious injuries in case of an accident a safety improvement of composite aircrafts is necessary.

During the “Safety-Box” project the crash behaviour of the airframe of the small four-seat aircraft “C4” of Flight Design GmbH, developed as composite design, is examined. Parallel to the development, experimental flight test and certification process of this new type of aircraft the project work influenced the design in the sense of increased occupant safety. To achieve significant safety improvements a draft for a “Safety-Box” concept was made, suitable crash elements were investigated and the overall composite structure was re-engineered. In order to be able to validate the effect of the structural modifications and changes the implementation of this developed concept into a C4 has to be accomplished and experimentally tested.

2. Crash Conditions

The scope of the project is to increase the overall safety of small composite aircraft, therefore the Flight Design C4 (Figure 1) is considered as a representative for a typical four-seat single engine aircraft up to a maximum takeoff weight of 1200 kg. The C4 has a wingspan of 9.93 m, a speed range from 50 to 160 kt and can reach a maximum range of 2200 km. The aircraft is designed in a high wing configuration with a fixed landing gear.

Figure 1. Flight Design C4 [1]

Typical real-world accidents have been evaluated in order to identify a representative crash scenario, that can be used during the analysis, and that offers real improvement for the later aircraft user due to it’s statistical real-life relevance. Accident investigation reports published by the German Federal Bureau of Aircraft Accident Investigation (Bundesstelle für Flugunfalluntersuchungen - BFU) have been analysed, and matched with the in-field accident experience of Flight Design from it’s fleet of 1.800 two-seat aircraft operated world-wide in 43 countries. Furthermore the AGATE program (Advanced General Aviation Transport Experiment), which also focused on occupant safety, was considered [3]. The design impact situation was determined with a velocity equal to the stall speed of the aircraft, in this case 50 kt, at a flight path with 30° nose down at impact. In-field experience shows that this provides a scenario that happens with a high statistical relevance, has the potential to be survivable, but results in fatal injuries all too often when using state-of-the-art aircraft as of today. The aircraft structure should hit a solid surface, like a concrete runway, representing a typical accident during takeoff or landing. At the same time this makes testing of this scenario much more easily repeatable and thereby comparable. Soft soil impacts are highly suspicious to uncontrollable variation in soil characteristic.

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3. Development of a Crash Resistant Aircraft Cabin

To provide a better survival chance for the occupants an overall crash concept for the complete aircraft should be developed. The so called “Safety-Box” should meet certain requirements to ensure less harmful impact conditions. First of all the Safety-Box should prevent the cabin from a complete collapse and provide a survival space. Nothing should be able to intrude the cabin and injure the occupants. To reduce the high accelerations on the passengers during the impact, kinetic energy has to be absorbed. Two main energy dissipating effects will be considered: energy absorption due to material damage and due to friction while the aircraft slides over the impact surface. Between the stiff passenger cell and the ground, energy can be absorbed by controlled material deformation and failure of the aircraft structure. The movement of the aircraft must not stop abruptly at the first contact with the impact surface. A slipping over the ground has to be encouraged and a digging into the ground or canting has to be avoided. To restrain the passengers inside the Safety-Box a crash prove seat system was developed.

Spaces in the fuselage beneath the cabin floor and in front of the firewall have been specified as possible energy absorbing zones. For the contact areas of fuselage and ground aluminium honeycombs have been identified as suitable crash elements to damp this hard contact. The engine has a high mass and thereby a high kinetic energy and a big risk potential. To reduce concentrated loads as at the engine mounting points crash tubes made from composites have been developed and characterised.

The aluminium honeycombs Plascore PAMG-XR1 5056 have orthotropic mechanical properties which have been determined in several tests considering tensile, compression and shear load cases. Based on this data an adapted material model for the FE code Abaqus was compiled and verified (Figure 2). This Abaqus material model is applicable with hexahedron volumetric elements and represents the orthotropic mechanical behaviour. Figure 2 shows a comparison of experimental and simulated data of a sample measuring 100 mm x 100 mm with a thickness of 25 mm. The load was applied lengthwise to the honeycomb cell direction in which the best energy absorption rate can be achieved.

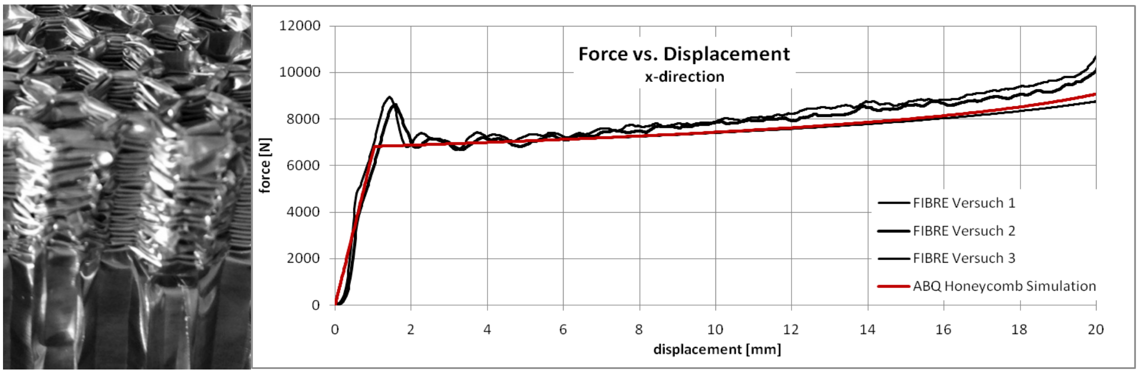

Figure 2. Honeycomb material model comparison [4]

The second investigated type of energy absorbing elements are crash tubes, which work well for locally concentrated loads. Several tubes with different composite lay-ups but same diameter of 50 mm were built and characterised in compression tests by their energy absorption capability. The most promising design consist of a stepped lay-up of unidirectional carbon fibres in load direction combined with woven carbon fibre fabrics orientated in 0°/90°. With this configuration a specific energy absorption of 79,6 J/g could be achieved [2]. The amount of layers, steps and length of the crash tube can be adapted to match the required energy intake. The stepping reduces the initial failure load and enables a high crushing level (Figure 3).

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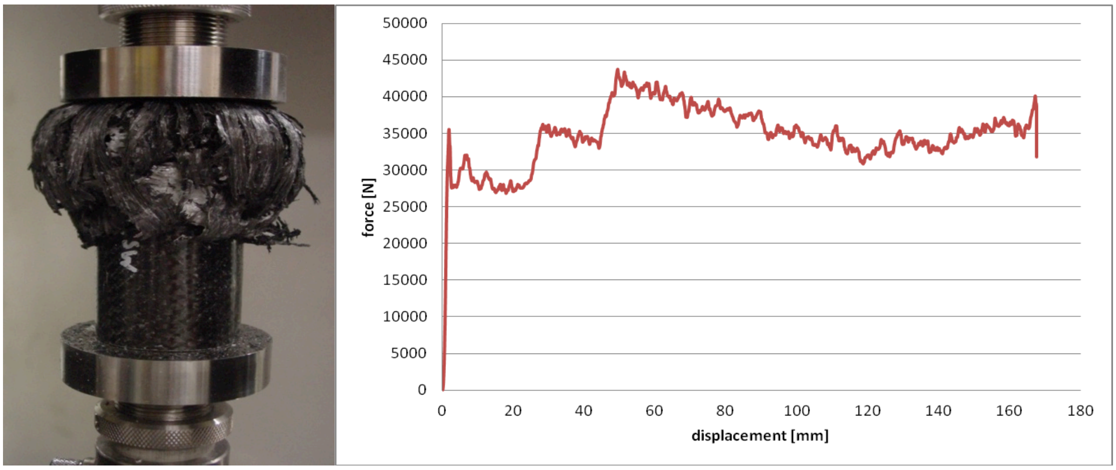

Figure 3. Crash tube crushing behaviour [2]

Besides the investigation of additional crash elements the primary structure of the aircraft and its crash relevant components had to be designed for an impact. Namely the main landing gear and the seats have been constructed as composite structures matching the EASA certification requirements CS-23.

4. Numerical Investigation of the Crash Behaviour of a Small Aircraft

The C4 was designed, build and tested by Flight Design in compliance with EASA CS-23 regulations, so that the primary structure is sufficient for operational flight conditions. These design requirements do not impose direct criteria to the airframe as such, considering the accident case defined for this investigation. The design improvement started with this first construction developed by Flight Design on the basis of CS-23, in order to get an idea for the crash behaviour of the C4 this structural concept. Subsequently the Safety-Box concept and the characterised crash elements had to be adapted and integrated into the C4 structure to improve the crashworthiness and increase occupant safety. A FE-model based on CAD data, lay-up plans and manufacturing instructions of the C4 was created. For the modelling and calculations the explicit code of Abaqus 6.14-2 by Dassault Systems was used. In order to evaluate and optimise the behaviour of the test aircraft C4 in the event of a crash, a simulation of the entire system with the defined crash conditions is necessary.

The impact surface was set to be solid, therefore it was represented by a flat and rigid surface, which was fixed by boundary conditions to be unmoveable. The vertical contact between elements of the aircraft and this rigid ground was defined as hard contact. For the sliding of these elements on the surface, a friction coefficient of 0.3 was set to correspond to the roughness of asphalt.

For the modelling of the overall C4 aircraft structure some assumptions and simplifications have been made, in order to keep the modelling and computational effort feasible. All parts and assemblies with a direct influence on the crash behaviour have been integrated into the simulation model as structural components. The wing, the elevator and other installations and systems, as for instance the fuel system, the doors, the avionic systems or the luggage, which do not affect the structure directly, have been integrated only as mass points into the simulation model and coupled to the structural model with constraints. Likewise the occupants and the seating systems, which had already been dimensioned in a separate FE analysis, were firstly inserted as mass points into the calculation model.

The modelling of the aircraft structure is based on CAD geometry and composite lay-up plans provided by Flight Design. The crash relevant structure consists essentially of the fuselage, the engine block including the engine mount and the landing gear. These components of the C4 aircraft have been

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geometrically modelled and assigned with structural and physical properties. The primary structure of the C4, which also includes the fuselage, is manufactured in a composite design. Before importing the CAD data into Abaqus, these geometries have been revised with the program CATIA, to make a performant meshing possible. In the FE model composite structures are represented by surface geometries. These surface geometries have been cut into different sections. Each section has been derived from the manufacturing data and sums up a specific lay-up for certain regions. The different composite lay-ups have been defined and referenced to the specific sections. The orthotropic mechanical properties of the composite materials, the orientation and the thickness of the specific ply and the stacking sequence were entered into the lamina definition. For the calculation and the analysis of the structure in the event of a crash a discretisation is necessary, that required meshing and coating the surfaces with two dimensional shell elements. This method was applied when modelling the fuselage structure. In addition to this simplified and discretised fuselage the main landing gear, which has been designed and modelled separately, was integrated into the FE model. Whereas the engine block was made of metal and consisted of solid cast and milled parts, it has been modelled as rigid body. The attachment of the engine to the fuselage was realized by an engine mount, which was build as a welded pipe framework. The nose gear is also connected by a metallic pipe framework with the fuselage. Geometrically these frameworks have been modelled as lines and then discretised with 1-D beam elements. The specific cross sections and material properties have been assigned to these elements. The complete FE model comprised over 64 000 elements with a mean element size of about 20 mm.

To correspond with the defined crash scenario the aircraft model was positioned on a 30° inclined path. A predefined field has been set to give the moving aircraft model the initial speed of 50 kt with the matching direction (Figure 4)

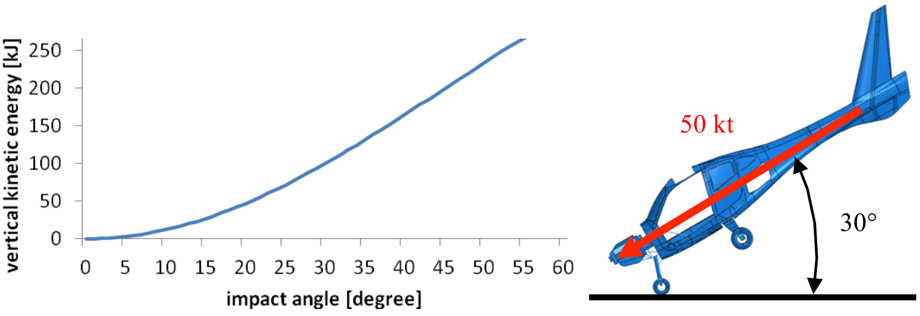

Figure 4. Impact angle and energy

For the composite structures special material and failure models have been applied. The linear elastic mechanical behaviour took account of the anisotropic properties of the fibre reinforced materials. The damage initiation for fibre reinforced composite materials in Abaqus is based on Hashin's theories and considers the initiation criterions: fibre tension, fibre compression, matrix tension and matrix compression. When exceeding a certain initiation criteria the associated element stiffness is linearly degraded from then on. The progress of degradation relies on the energy dissipation during the damage process. As reaching a degradation rate of 0.995 resulting in very low maintaining element stiffness, this element will be deleted form the mesh. These described models enable the simulation of the failure behaviour for composite materials.

First simulations of the defined crash scenario revealed that the baseline structure of the C4 could not withstand these harsh impact conditions and catastrophically failed (Figure 5). Severe danger to life for the aircraft's occupants could be caused by the engine block intruding into the cabin and by the top mounted wing loading and crushing the cabin. In addition the lower structure of the cabin and

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especially the floor would break on impact with the ground. The cabin, which should provide a survival space under crash conditions for the occupants, would be completely destroyed. These crash simulations of the initial C4 design made the necessity of structural improvements obvious. These identified critical regions had to be investigated and modified to increase the overall crash safety.

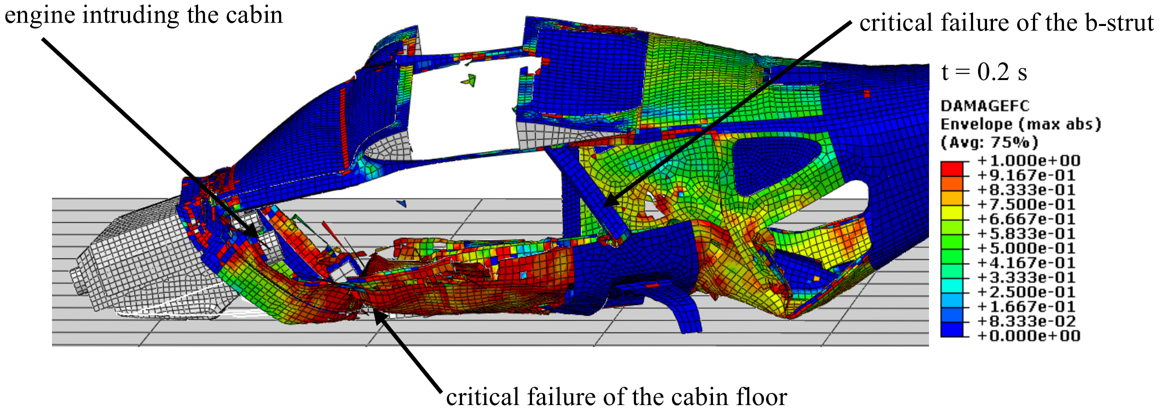

Figure 5. Crash simulation results of baseline design: element degradation due to fibre compression

Resting on the analysis of the initial C4 design by Flight Design and the developed concept for the Safety-Box the structure of the aircraft had been revised. Therefore the fuselage structure was stiffened with additional composite frames to withstand the load of the top attached wing and to preserve the integrity of the cabin (Figure 6). To absorb energy and to damp the impact the investigated aluminium honeycombs have been integrated into the fuselage between this stiff Safety-Box and the fuselage skin. These changes led to a cabin which could provide a survival space for the occupants, and an energy absorbing area in front of and beneath the cabin.

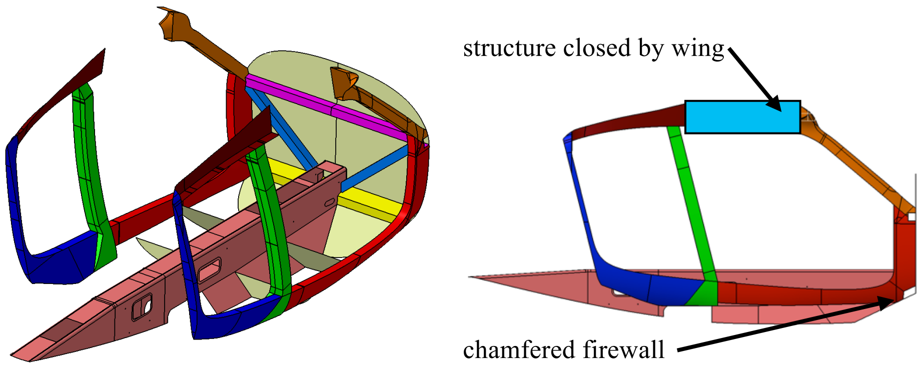

Figure 6. Safety-Box consisting of crash frames

The structural concept with the improved crashworthiness was developed during several iterative loops of structural modifications and crash simulations. Critical areas have been analysed and edited step by step to see the effects on the overall crashing behaviour. The tunnel in the middle of the cabin was completely revised. First, the tunnel was stiffened to stabilize the cabin together with the additional frames at the sides. Second, the tunnel structure beneath and in front of the cabin was weakened to be able to deform and absorb energy. The failure initiation principle of the investigated crash tubes was applied to the front of the tunnel. The lamina was stepped, with the result that the structure at the front is weakened, in order to trigger initial failure at this position and in a controlled way with progressive strength increase. This predetermined breaking point shifts the region of failure with potentially dangerous composite structure fragments as far as possible away from the occupants. The lower edge of the firewall has been chamfered to facilitate the fuselage to slide along the ground, instead of digging in with an abrupt stop (Figure 6).

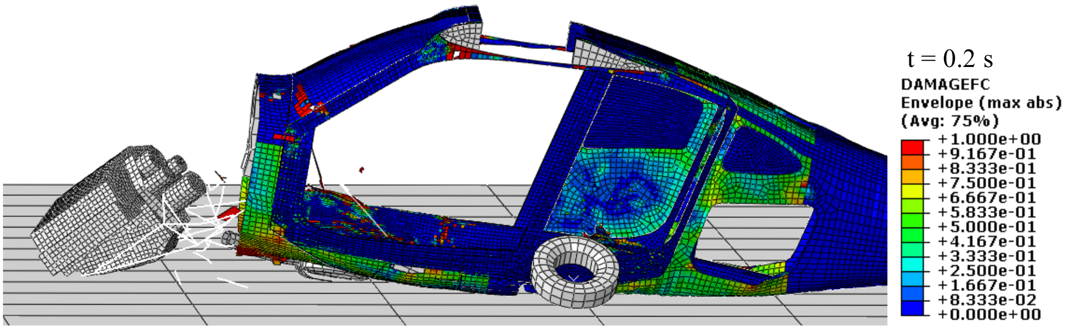

Figure 7. Crash simulation results of improved design: element degradation due to fibre compression

The simulation results show, that the improved structure provides a much better crash behaviour and that the cabin can withstand the impact (Figure 7). An improved occupant protection by providing a surviving space has been established, but in order to estimate the influence on the health the accelerations during the crash have to be considered as well. Most harmful to the human body are vertical accelerations. With the developed Safety-Box the exposure to the pilot can be kept below the injurious threshold of 45 g, which the human body can stand for a duration of maximum 0.05 s with moderate injury. The vertical accelerations, which have been displayed for the pilot's centre of gravity position and filtered with a butterworth algorithm (200 Hz), reflect the different stages of energy absorption during the crash (Figure 8). The simulation results reveal the potential of improvement for the Safety-Box concept with the conclusion, that it should be possible to survive these crash conditions with the improved airframe structure. The additional mass regarding to this safety concept is estimated to be around 40 kg.

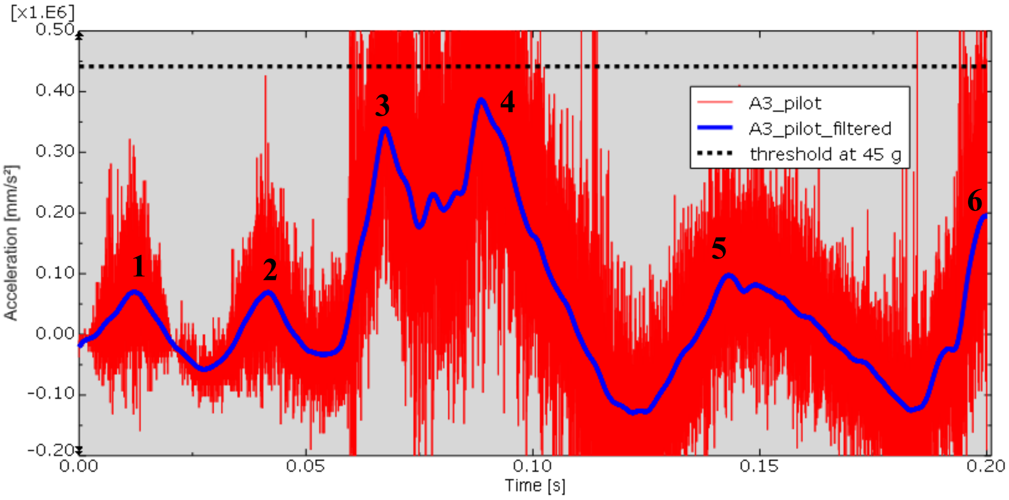

Figure 8. Vertical accelerations of the pilot during the crash: (1) impact of the front wheel; (2) impact of the engine block; (3) crash of the engine into the fuselage; (4) impact of the fuselage; (5) failure of the main landing gear; (6) impact of the tail on the ground

6. Outlook and Further Steps

The structural modifications devised in iterative simulations of the C4 structure will be experimentally tested under the defined impact conditions. The experimental test set up consists of auto cranes which were used to create a pendulum swing (Figure 9). Via cables the test aircraft is attached to a high mounting point on a crane, so that it will crash under the defined conditions (30° and 50 kt). With another crane the aircraft is pulled back and upwards. During the crash accelerations and high speed videos will be recorded to analyse the crashing behaviour of the improved structure and to compare this data to the simulation results. Based on these investigations guidelines to improve the crash performance for further aircraft designs will be derived and discussed with the relevant aviation authorities and the with industry standardisation bodies.

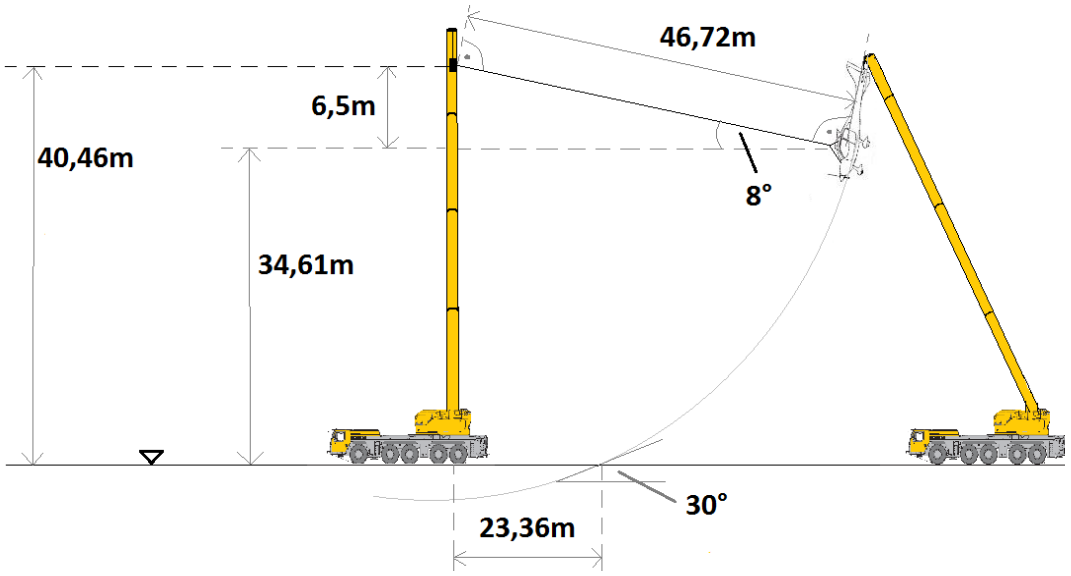

Figure 9. Crash test set-up

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