Impact damage has been known to seriously limit the performance of composite aircraft structures. In the preliminary design phase, tens of thousands of subparts need to be analyzed for impact. Over the years, many approaches have been proposed to study the creation of impact damage and to determine the residual strength of the structure. Although the progress has been significant, most of the existent methods are too prohibitive for large-scale implementation in the industry. In this thesis study, efficient analytical models were developed to study impact damage. These models will help the designer in the preliminary design phase to perform quick trade-offs and multiple analyses.

THE CHALLENGE
Impact damage modeling in composites is challenging for two reasons: The overall damage state is very complex and different types of failure must be modeled. Furthermore, the problem is dynamic, which means that after onset of damage the stiffness properties must be updated, after which the load is increased.

The thesis was broken into two parts: damage resistance and damage tolerance. “Please, think it over well, if you really want to get into this thesis”, said my supervisor. He emphasized that this was not going to be the average kind of work.

DAMAGE RESISTANCE AND DAMAGE TOLERANCE
In the seventies, Cairns and Lagacé (Cairns & Lagacé, 1989) developed the notion of damage resistance and damage tolerance at MIT. Damage resistance in this context deals with the amount of damage a composite structure sustains for a given impact load. Damage tolerance deals with the residual failure load of the damaged structure. Previous work on these two topics included work done by Sun and Chattopadhyay (Sun & Chattopadhyay, 1975), Cairns and Lagacé (Cairns & Lagacé, 1989), Olsson (Olsson, 2001) and Talagani (Talagani, 2013). These efforts ranged from simple curve fits to very detailed finite element analyses using cohesive elements. Simple curve fits do not really add to the understanding of the problem and previous work showed that a detailed finite element analyses could take a couple of days to run (Talagani, 2013).

ANALYTICAL METHODS TO MODEL IMPACT DAMAGE
In this thesis, analytical methods were developed for two purposes: To model the types, amount and location of impact damage (damage resistance) and to determine the residual compression strength of a composite laminate (damage tolerance). These analytical models should be used in the preliminary design phase avoiding expensive finite element analyses and/or test programs. When developing analytical methods, one needs to be aware of the following: out of ten potential methods, only one or none actually works. Analytical methods are simplified involving many assumptions. The question is: how valid are the assumptions made? This question is answered by verifying the model with numerical methods and/or by validating the model using test data. What makes a good engineer is being ready to make the proper assumptions. What makes a great engineer is being ready to abandon these assumptions and search for the right ones. Although different kinds of impact problems exist, this work is limited to quasi-static impact. This is the case when the impactor mass is...
IMPACT LOAD AND STRESSES
Considering a composite plate impacted by a spherical object, the impact load is typically modeled as a point load. This load is applied in out-of-plane direction and will cause stresses through the thickness of the plate. By the principle of energy balance, the impact load can be determined. One can now solve for the stresses using the finite element method. This can be computationally expensive requiring a fine mesh with element dimensions in the order of 0.05mm in the contact area (Talagani, 2013). In this thesis study, exponential functions were used in an assumed form for the out-of-plane stresses. Using energy minimization, the other stresses and unknowns were solved for. The analytical method as implemented in MATLAB takes three seconds to run and it showed to agree well with finite element results. This means that one can avoid long finite element simulations by using this model. The assumptions made here seemed to be valid for a wide range of parameters.

DAMAGE SIZE DETERMINATION
Moving on to impact damage modeling, simple failure criterion was used to determine different types of damage. Any damage creation before the peak impact load reached was neglected here. By the principle of energy balance, the damage created at the peak impact load was determined by modifying the previously determined stresses according to their strength allowances. The big question was: Is this assumption a reasonable one? If it is, it means a simple model can be used to determine impact damage accurately neglecting damage creation and stiffness loss before the peak load is reached. From a validation with test results published by Dost et al. (Dost, 1991) it was found that the damage contours, for example delaminations at the interfaces of plies, fiber breakage, and transverse matrix cracks, were captured quite accurately. Figure 1 for a comparison of the analysis model prediction with the damage contours obtained from an ultrasonic C-scan of a damaged quasi-isotropic laminate. For some cases however, the discrepancies were significant.

RESIDUAL STRENGTH DETERMINATION
It is recognized that the models that have been developed so far in the thesis study were simplified and as such, they were not valid for all cases. At that point, three to four months passed from the kick-off meeting, taking into account that two months were only spent on an approach that eventually did not work. Only two months of the actual work resulted into a damage resistance model. A decision had to be made here: Do we start refining the damage resistance model to make it more versatile? As the model refinement seemed to be out of the scope of this thesis, the answer was obvious and we moved on to set up a damage tolerance model in order to determine the residual strength of the damaged composite. The damaged region of the laminate was modeled as several concentric ellipses of different stiffness and strength. This difference in stiffness will give rise to stress concentrations when the laminate is loaded under uni-axial compression. Figure 2 depicts the stress concentration in the damaged region consisting of three elliptical inclusions. As the elliptical boundaries are reached, a drop in the stress can be observed. This is attributed to the lower stiffness encountered in these regions. One can imagine that the difference in strength may cause some ellipses to fail and redistribute the load to other ellipses until the entire laminate fails as a whole. To determine the failure load, or the residual strength, of the damaged laminate, a progressive damage analysis was carried out.

PROGRESSIVE DAMAGE ANALYSIS
At the damage site, delaminations and transverse matrix cracks can coalesce in individual smaller laminates, or sub laminates. As the laminate is loaded under compression, the sub laminates can buckle, ultimately leading to final failure. In the analysis model, local buckling was not captured and this would have implications on the failure load predictions when compared to test data. The failure load was determined in an iterative procedure: Apply a small compression load, check which ellipse fails, adjust stiffness/strength properties, increase the load and continue the iteration until the laminate fails as a whole. When an ellipse fails, it becomes equivalent to an open hole, increasing the local stress concentrations. Failure of an ellipse was assessed by using a first ply failure criterion. See figure 4 for the comparison of the predicted failure load with published test results from Dost et al. (Dost, 1991) for a quasi-isotropic laminate.

CONCLUSIONS
The efficiency of the models created make them prime candidates, when refined further, for trade studies and optimization. They can form the basis to accurately predict the compression after impact strength of quasi-isotropic laminates.

References