Iterative Determination of Save Working Loads (SWL) for Crawler Cranes

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Summary:

A program for the calculation of Save Working Loads (SWL) is introduced. It uses ANSYS and its parametric design language. The models are based on large displacements, small strains and linear-elastic material. The limit state method with partial safety coefficients is applied. For a crawler crane many configurations exist and they have to be calculated for different positions and load cases.
Special attention is paid to the overall structural stability of the crane and to the effectiveness of the calculations.

Keywords:

save working load, structural stability, limit state method

1 Introduction

Lattice boom crawler cranes (fig.1) have different applications and therefore different configurations.

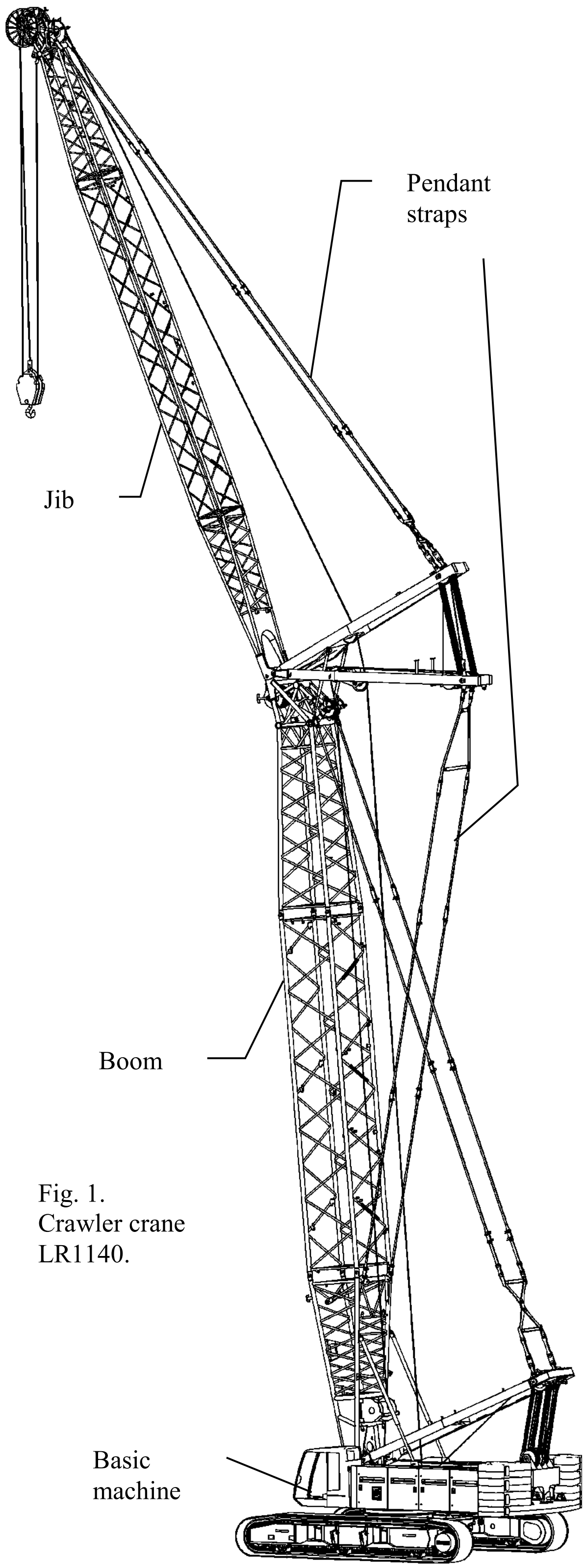

Fig. 1.
Crawler crane
LR1140.

1.1 Geometric Configurations

A crane can operate with boom only or with boom and jib. Both, the boom and the jib can have different lengths. The length can be changed by assembling more or less boom or jib sections (in fig.1 both boom and jib have only one section). The boom and jib sections are of different lengths, e.g. 3m, 6m, 12m.

The hoisted load depends essentially on the hoist rope reeving (on fig.1 we have 3-fall reeving on the jib). With less reeving the lifting capacity is reduced by the nominal load of the hoisting winch, but the hoisting speed is faster and the dynamic effects from hoisting are stronger.

In addition, the crane can operate at different angles or which is equivalent, at different working radii.

For all this situations a Save Working Load (SWL) have to be determined. The SWL is limited by two main factors:

- rigid body stability
- structural design limits

The rigid body stability calculations are comparatively simple and not time intensive – they are performed on an undeformed system. After determination of the overall mass and center of gravity the rigid body stability calculations are performed in accordance to the valid standards [1-3].

1.2 Structural Calculations

The structural calculations are performed according to the valid standards for Europe [1,2] and USA [3]. In this standards different load cases are considered. The main load for the structure comes from hoisting and dead weight. But there are many other effects, which have to be considered:

- dynamic effects from hoisting itself – on the load and on the dead weight
- dynamic effects from other movements: slewing, luffing etc.
- not exact horizontal ground – trimm and heel
- not exact vertical load – sidelead and offlead
- wind

The limit state method with partial safety coefficients is applied. In accordance with this method the loads are multiplied with the partial load coefficients that are different for different loads and load cases [1,2].

For each component design limits are defined. They are equal to the limiting force divided by the partial resistance coefficient. For the boom and jib sections design limits for the chords and diagonals are calculated. For many of the pivot points (e.g. between the jib and the boom, between the boom

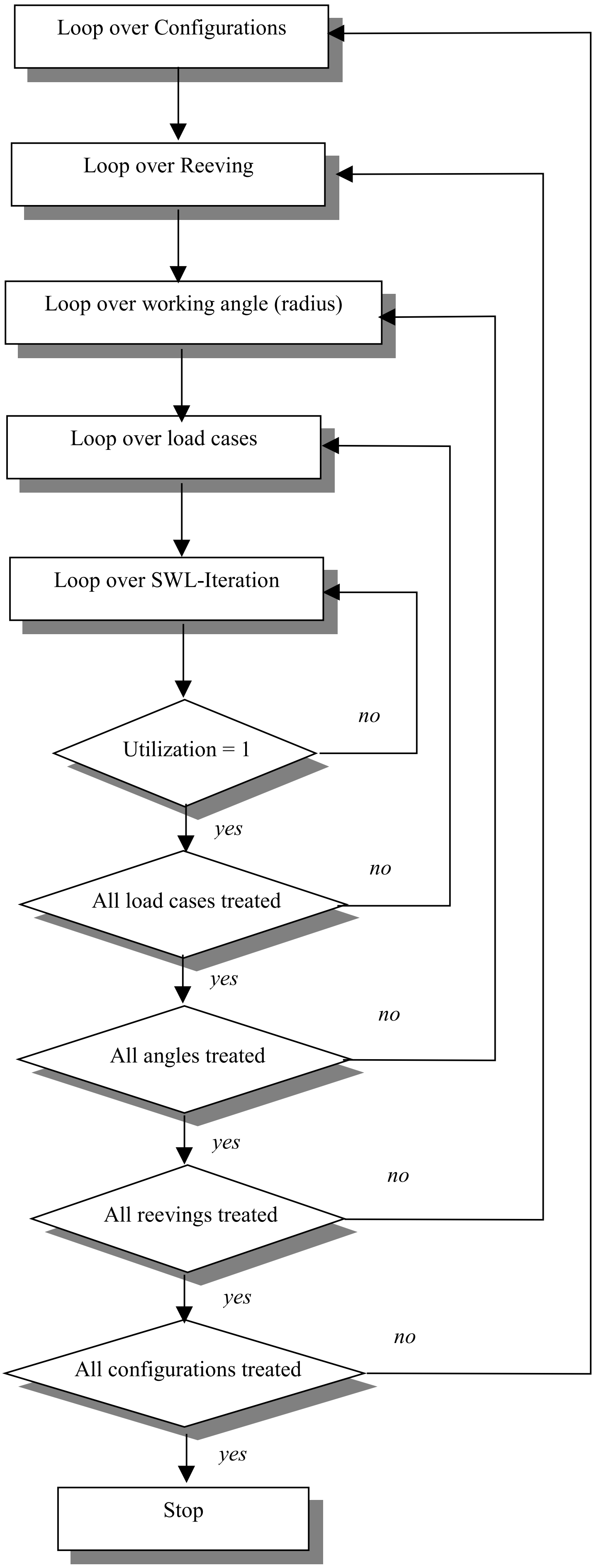

Fig.2. Structural SWL-calculations

and the basic structure etc.), for the slewing bearing, for pendant straps etc. are defined design limits, too. A crucial design limit, especially for longer configurations at steep positions (small working radii) is the overall structural stability of the crane.

The hoisted load is changed iteratively until the maximum utilization of all design limits is equal 1. The tolerance can be varied, but usual tolerance is between 0,990 and 1,000. The minimum hoisted load from all load cases is the structural SWL for this situation.

The scheme of the structural SWL-calculations is shown in fig.2. After this calculations the minimum from structural SWL and rigid body stability SWL is the final SWL.

Due to the contradictory requirements for low weight (that determines good rigid body stability SWL) and high strength (that determines good structural SWL), a very lightweight construction for the boom and the jib is necessary. This is achieved by the form of the structure – it is a lattice construction, consisting of chords (that transferred the normal force and the bending moments) and of diagonals (that transferred the shear forces and the torsional moment). For the same reason high yield strength structural steels are used for the boom, the jib and the pendant straps, like StE960, StE770 and StE690.

All calculations are carried out using the ANSYS Parametric Design Language (APDL) [4], usually in batch mode.

2 Model and SWL-Iteration

There are five nested loops that have to be passed. It is not possible to use superposition for the different loads, because the crane structure behaves nonlinear - the longer the boom/jib, the stronger the nonlinear effects. For each pass of the most inner loop a geometrically nonlinear problem with linear elastic material is solved. But the strains are small and the problem can be classified as relatively weak nonlinear.

The aim is to decrease the computational time. Therefore the lattice boom/jib sections are reduced to beams with corresponding stiffness. The basic machine with the crawlers is simulated with few beam elements as well. BEAM4 and MASS21 elements are used for the structural steelwork. For the ropes and for the pendant straps LINK11 and LINK10 elements are used. The model for the same configuration as in fig.1 but the jib at a flat angle is shown in fig. 3.

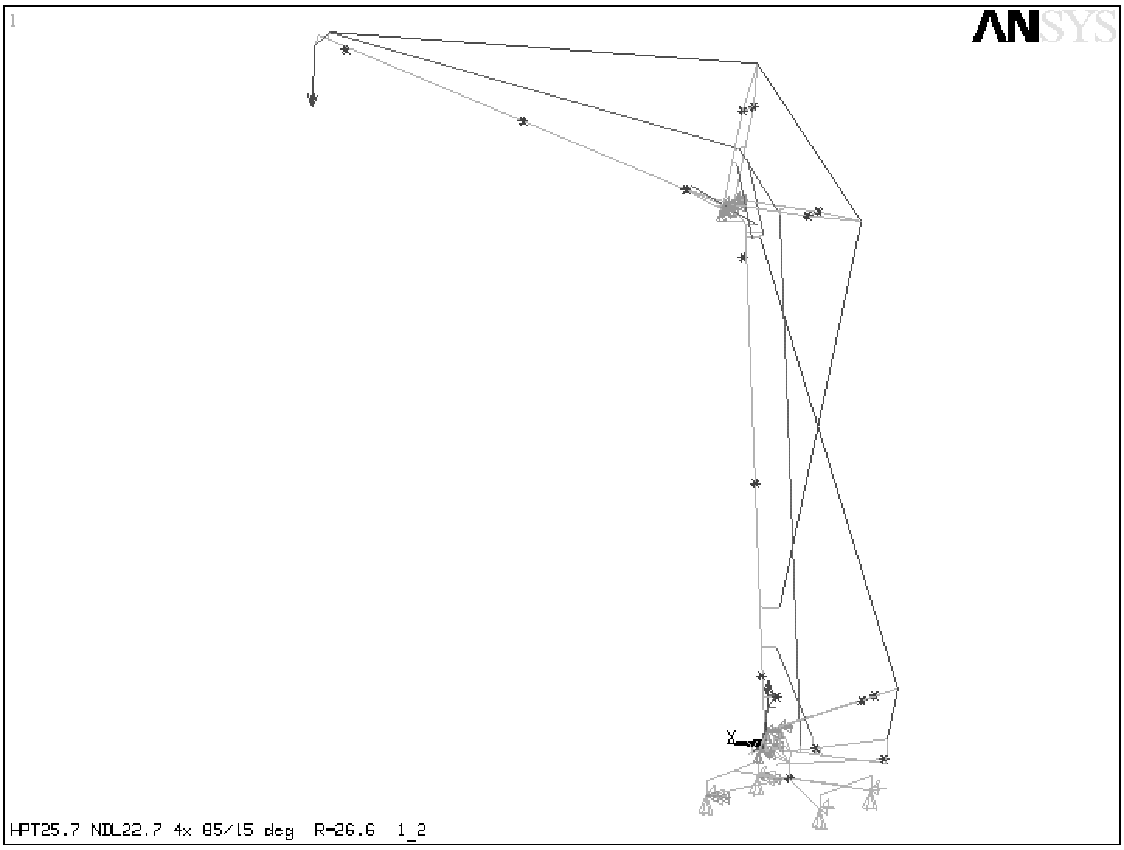

Fig.3. Model of a crane.

The loads due to dead weights, crane movements like slewing and luffing and wind on the structure remain constant for different hoisting loads. But with a change of the hoisting load the dynamic effects on the load and on the structure, the force in the hoisting rope and the wind on the hoisting load changed as well. All constant loads are applied in a first load step with a part of the assumed hoisting load. In a second load step only the hoisting load and the corresponding load are increased.

After solving the model with all actual loads, all design limits are checked and the maximum utilization is calculated for all substeps of both load steps. Usually results are available for at least three substeps (table 1). Then a quadratic approximation with the aim to estimate the maximum possible hoisting load for this load case is made (fig.4), using three substeps with a utilization near 1. In special cases (e.g. too less substeps, utilization bigger 1 after the first load step) only a linear approximation is made.

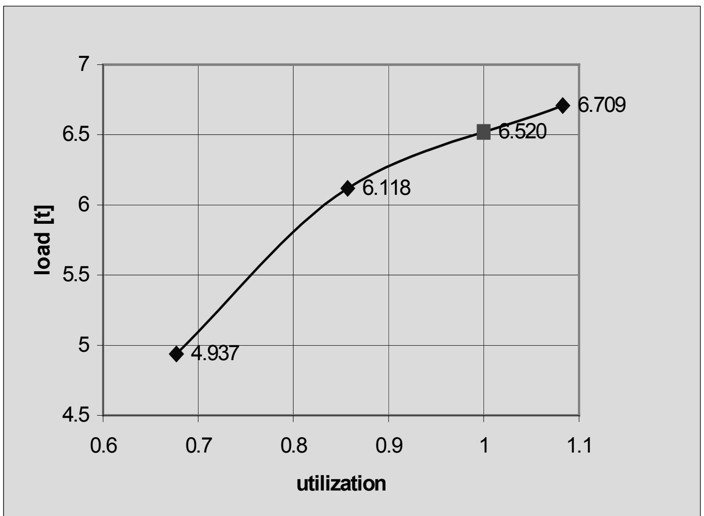

Fig.4. Approximation of SWL

Utilization	SWL	
0.677	4.937	calculated
0.857	6.118	calculated
1.083	6.709	calculated
1.000	6.520	approximated

Table 1. Approximation of SWL.

Usually after some iterations the utilization is ≈1 within the prescribed tolerance. If the crucial design limit changes near the utilization=1 the iteration process do not converge fast. In such cases a linear approximation with more substeps leads faster to a result.

3 Overall structural stability

The overall structural stability, in contrast with the other design limits, depends on configuration, reeving, working radius and load case. There are two possibilities to determinate it [4]:
- eigenvalue buckling analysis
- nonlinear buckling analysis

3.1 Eigenvalue buckling load

The eigenvalue buckling load is calculated relatively fast and for this reason it is calculated for each load case. It is usually bigger than the real buckling load. Therefore it is a good starting value for the SWL-iteration. The eigenvalue buckling load is calculated iteratively until the eigenvalue is nearly 1 with the aim to represent correct the constant loads (e.g. dead weight).

3.2 Nonlinear buckling load

The nonlinear buckling load is calculated as the last convergent load that the structure can carry without loss of stability. At the first load step all constant loads with a small hoisting load are applied. This leads to a deformed system and therefore no additional geometrical imperfections are applied. In the second load step the hoisting load is increased until the system does not converge. Auto time stepping is used with a minimal increment. The calculation of the nonlinear buckling load for each load case is generally expensive, because the last substeps result only in a small increasing of the hoisting load but need very much substeps. The number of equilibrium iteration increases rapidly with smaller increment and a balance is necessary to achieve a good, but not too expensive solution.

After determination of the nonlinear buckling load, the corresponding design limit is defined by dividing the nonlinear buckling load by the partial resistance coefficient.

4 Effectiveness of the calculations

The effectiveness of the calculations depends on many factors. In this section some actions for increasing the effectiveness are considered.

4.1 Initial and/or maximum values for the SWL-iteration

It is not very helpful to define one start value for all load cases, working angles and configurations because the real SWL varies in large margins, even for the same configuration.

The main idea in this section is to define actions that avoid the explicit calculation of the nonlinear buckling load for all load cases, but guarantee sufficient safety against overall buckling. The maximum SWL can be limited previous to the calculations by the design limit for the winch (it can be turned on/off) and/or by a maximum load (input parameter). During the calculations the maximum value for the SWL can also be limited, e.g. from previous load case or minimum rigid body stability load (s. below). To guarantee the safety against overall buckling the maximum SWL (wherever the limit comes from) is multiplied by the partial resistance coefficient and a calculation with this value is performed. If the solution converges, this is accepted as sufficient safety against overall buckling. The nonlinear buckling load is not calculated explicitly – the calculation are not continued until nonconvergence. This saves a great amount of time due to the many substeps and equilibrium iterations near the convergence load.

4.1.1 Minimum rigid body stability load

For a good balanced structure the minimum rigid body stability load is not very far from the structural SWL and can be used as an initial value for the SWL-Iteration (s.fig.5).

In many situations the minimum rigid body stability load is crucial for the final SWL – e.g. long boom without jib at great working radii. For such situations there is an optional possibility to use the minimum rigid body stability load as an overall design limit. With this option on calculations until explicit nonconvergence are avoided. All other design limits are checked for a hoisting load equal to the minimum rigid body stability load multiplied by a coefficient and if the utilization of all design limits is less then 1, this is the final structural SWL.

4.1.2 Eigenvalue buckling load

The eigenvalue buckling load is used as a maximum value for the nonlinear buckling analysis, if nothing else limits the maximum load. Our experience shows that for steep boom positions it is only slightly bigger than the nonlinear buckling load (e.g. some percent), for flat boom position the eigenbuckling load is much bigger than the nonlinear buckling load (e.g. some times).

As it is pointed out in [4], the eigenvalue buckling analysis yields usually non conservative results. Our experience up to now confirms this – the eigebuckling load was always bigger than the nonlinear buckling load.

4.1.3 SWL from previous load case

After the first load case the determined SWL can be used as an initial value and at the same time as maximum value for all other load cases. The time saving depends on the sequence of the load cases. The most time saving is when the first load case is mostly the crucial. This cannot be achieved for all configurations simultaneously, but for a set of configurations it is possible to reorder the load cases so, that the most crucial is the first or the second.

4.1.4 SWL from previous working radius

Due to the procedure in our program, first is calculated the SWL for the smallest working radius (steepest position). Usually the SWL decreases with the working radius (fig.5). Therefore the SWL from previous working radius can be used as an initial value for the first load case of the next working radius.

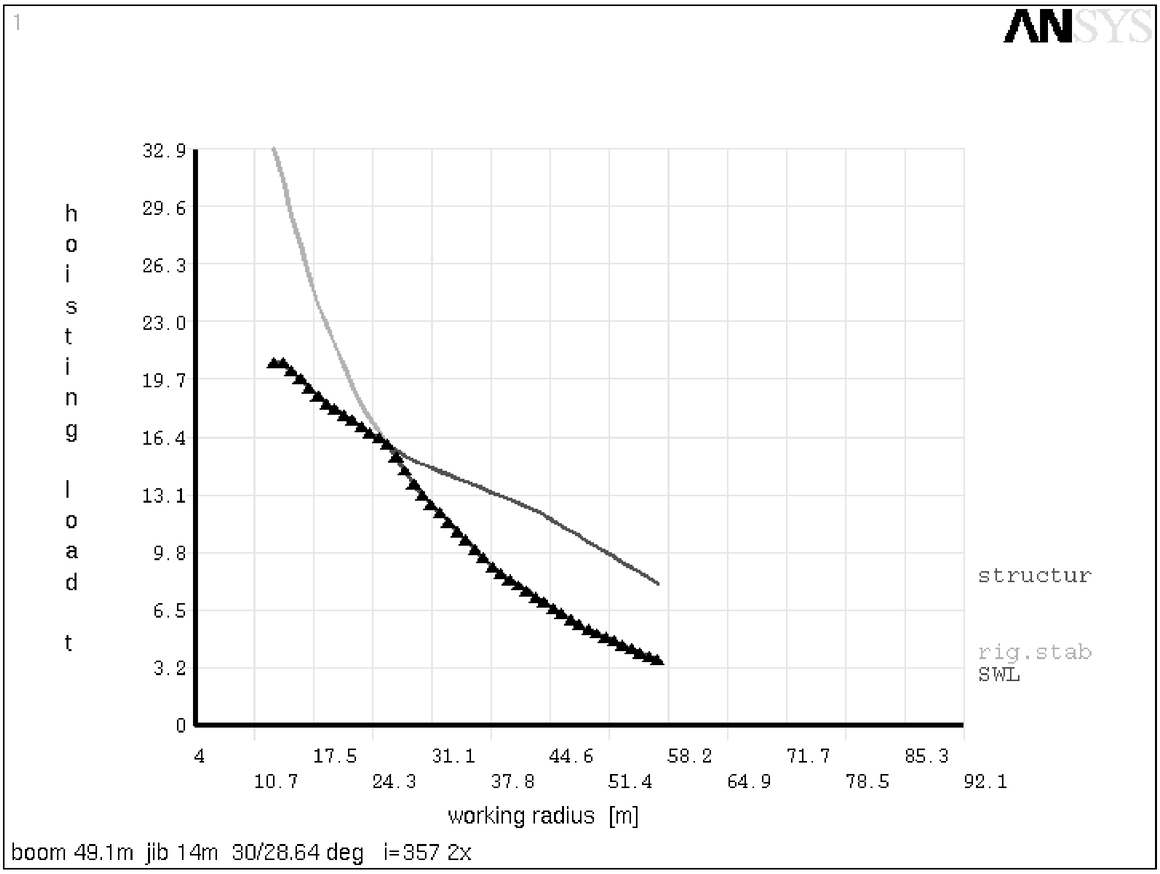

Fig.5. Rigid body stability load, structural load and SWL.

4.2 Interpolation between substeps

The calculations for both load steps are performed by substeps. Usually in the second load step are calculated more substeps. This is useful for a better approximation of the SWL for the next iteration (s. section 2). But ANSYS can interpolate linearly between substeps and we use this as an option. If this option turned on a check is performed whether an interpolation is eligible. A quadratic and a linear approximations for the next iteration are made. If their difference is less than a prescribed tolerance, e.g. 0,3% if the same design limit is crucial for all substeps and 0,2% for different design limits, then an interpolation can be performed.

The use of this option saves time, because only postprocessing operations are performed, no calculation. But there are cases where a check of the results with prescribed SWL, obtained within a previous iteration run, leads to utilization not within the prescribed tolerance. Therefore this option is used with caution, mostly for preliminary calculations. For the final calculations of the SWL this option is usually turned off.

4.3 Long time calculations

When the geometry of a new crane is finally specified, the SWL have to be calculated for all situations. This takes usually several weeks. Therefore we created a shell procedure for the loop over the configurations. It closes ANSYS after each configuration and starts it again for the next configuration. The information which configuration is finished is written in a file. This increases the reliability of the program, when the calculation is irregularly aborted due to external reasons.

5 Conclusions

A very efficient software tool based on ANSYS and their macro-language is presented. We use this tool to determine lifting capacities (SWL) for our crawler cranes and loads for the design of separate parts of the cranes. The software is continuously developed and extended. This is necessary among other reasons due to changes in the actual standards for cranes.

In contrast to complete self developed tools, we can use all features of ANSYS. For example we can use new elements from the ANSYS element library or new solvers. We can as well easily extend our crane model in a desired direction, e.g. to perform dynamic calculations. The combination of the programming possibilities of the macro-language with the features of ANSYS proved to be a very flexible and efficient tool.

6 References

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