Mistake-Proof Simulation

Design of experiments helps to create more robust products by accounting for noncompliance with design specifications.

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Engineering simulation is commonly used in the industry to capture the performance of a structure when it is 100 percent compliant with design specifications — for example, when every weld is perfect. The problem is that, for complex structures in the real world, not every weld can be expected to be non-redundant. When this noncompliance is not taken into account, structures sometimes distribute loads in ways that are entirely different from that predicted by analysis.

The author has developed a new approach to structural analysis that considers the effects of weld redundancy and, in particular, identifies the critical welds for which variation from specification could lead to significant and even catastrophic consequences. By identifying these worst-case load distribution paths, it was possible to redesign the structure to make it more robust. Additional quality improvements can be realized by focusing inspection resources on the most critical welds.

HOPING FOR THE BEST

Finite element analysis (FEA) plays a critical role in the design of most every complex structure, predicting the ability of the structure to withstand specified loads. FEA is nearly always performed based on the design specification. For a complex component, like the chassis of off-highway equipment with hundreds of manual welds, this traditionally has meant that the simulation assumes that every one of these welds is non-redundant as per the specification.

In the real world, it is almost impossible to ensure that every weld in the assembly is non-redundant, at times due to the fact that it is not possible to visualize this weld redundancy. But which welds are not compliant makes a great deal of difference to the structure's performance. There are relatively small numbers of critical welds where noncompliance could lead to new failure modes that cause substantial reductions in the structure's load-carrying ability.

The author has developed a method for identifying which welds are critical to a complex assembly. The example used is an off-highway vehicle chassis. The initial ANSYS Mechanical FEA model was set up using the traditional approach, with each weld as per the specification. The results showed the response of the structure and corresponding stress–strain distribution for the 100 percent-compliant design.

PARAMETRIC ANALYSIS EVALUATES IMPACT OF WELD REDUNDANCY

The author performed parametric analysis to evaluate the effects of partial and complete weld redundancy of various welds. Using the ANSYS Workbench environment makes parametric analysis a simple extension of a single simulation. In this case, welds were modeled with shell elements, so partial redundancy was simulated by proportionately decreasing the assigned shell element thickness for the weld elements, and absolute redundancy was simulated by deleting the shell elements that represent the weld. In cases in which welds were modeled using contact formulations, partial redundancy could be simulated by proportionately decreasing the pinball radius, and absolute redundancy by deleting the contact formulation.

In this example, to keep simulation time manageable, the author divided the welds into three categories utilizing input from several R&D groups: designers, based on preliminary hand calculations used to size the welds; manufacturing engineers, based on welds that are difficult to inspect; and test engineers, based on results from the test mule or prototype.

The most important 10 percent of welds were selected as high-impact critical welds; these were not simulated for redundancy because of their obvious importance. The bottom 60 percent of welds were designated as low-impact welds. Though they were not simulated for noncompliance, their redundancy was accounted for by considering weld adequacy during manufacturing. The remaining 30 percent of the welds, whose importance was unclear, were simulated for redundancy.

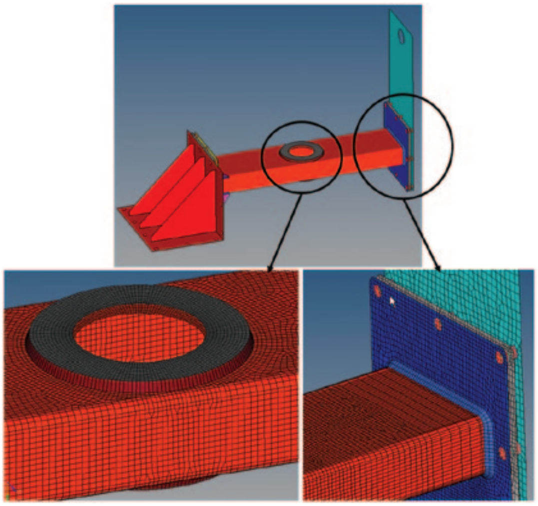
Of the 14 welds that were selected for parametric analysis, nine are located on the front of the chassis, and five are in the rear. The front welds have very little influence on the strain distribution in the rear half of the chassis and vice versa, so the number of iterations required to evaluate these welds was reduced by considering the front and rear welds in separate experiments.

The author used a design of experiments method to configure a series of runs to explore the complete design space and evaluate the structure's performance based on a relatively small number of FEA iterations. In each iteration, the author assumed that one or more welds were partially or fully redundant for the purposes of the analysis. All of the simulations were performed on a high-performance computing (HPC) cluster.

PARAMETRIC PERSISTENCE SAVES TIME

Parametric persistence made it possible to automate the parametric analysis process simply by giving ANSYS Workbench a table of varying parameters. When a parameter was changed, ANSYS meshing tools re-applied the previous setup, including mesh distributions specific to the changed entities. When the update all button was clicked in the design point widget, the first design point (with the first set of parameter values) was sent to the parameter manager in Workbench. This drove the changes to the model from CAD system to post-processing.

ANSYS solvers re-applied the setup and solved the new model. The new design point was simulated, and output results were passed to the design point table, where they are stored. File transfer, mapping between physics, and boundary conditions remained persistent during the update. The post-processor then regenerated all the images, tables, animations and reports. The process continued until all design points were solved, defining the design space for further analysis. This automated process reduced the time required to compare different designs.



Typical FEA model with welds modeled using shell elements

RESPONSE SURFACE MODEL

The results included a response surface model that showed how each of the welds contributed to strain; the model also estimated

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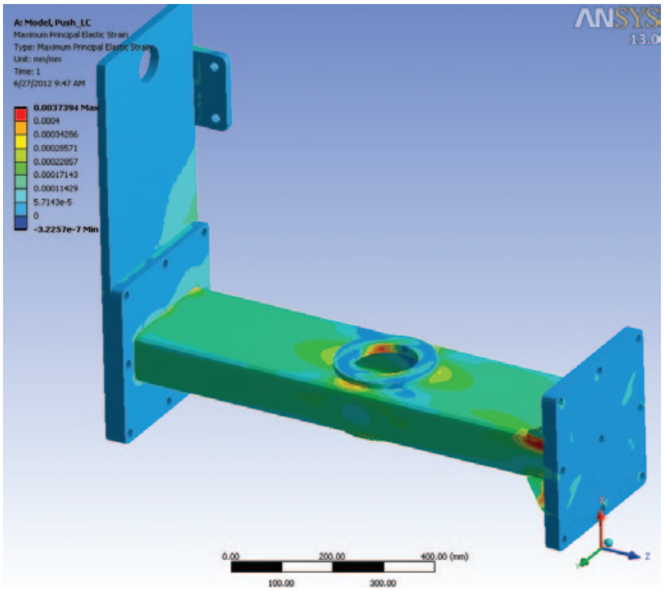
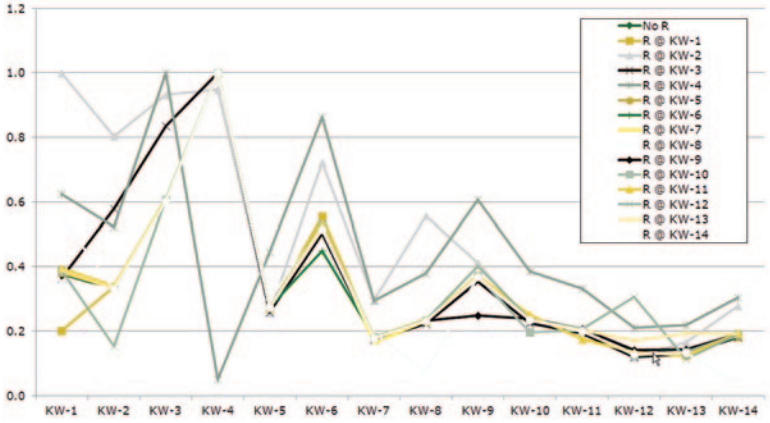
the performance of the design with every possible combination of welds missing. The response surface model was used to predict approximate maximum principle strain at each of the 14 key welds as a function of compliance of each of the welds. Statistical analysis was used to determine the worst strain condition for each key weld. Pareto analysis based on FEA results showed the most significant contributors to strain at each location and which variables could be eliminated without influencing the statistical validity of the response surface model.

For example, the highest strains at weld 9 occurred when weld 9 is compliant, weld 12 is redundant and weld 13 is redundant. For the above weld compliance status, the strains at weld 9 for torsion counterclockwise loads are 0.419, compared to 0.369 for 100 percent compliance. Only five key welds from the front of the chassis and two key welds from the rear generate a 15 percent change in strain when absolutely redundant. These welds were added to the list of most-critical welds in the structure that were selected manually.

Identifying the most critical welds provided critical guidance in redesigning the structure to increase its robustness. Furthermore, this approach helped to prioritize the importance of welds, so that inspection time can be devoted to the welds that are most important. All critical welds are thoroughly inspected for conformity to specification, including weld size, weld length, wrap, porosity and undercut. Even the slightest nonconformance of a critical high-impact weld requires scrapping the entire assembly. Considering worst-case redundancy in structural analysis helps to ensure that every single product that rolls off the line exceeds customer expectations.



Stress analysis results help to visualize performance of weld subjected to clockwise torsion load.



Overview of strain data vs. noncompliance of 14 welds evaluated shows wide variation in importance of different welds.

Considering worst-case redundancy in structural analysis helps to ensure that every product exceeds customer expectations.

Location	LC	KW-9	KW-12	KW-13	Strains with Redundancy	Strains without Redundancy	% Change
W9	CCW	R	NR	R	0.820	0.824	-0.4
	CW	R	NR	NR	0.713	0.681	4.7
W10	CCW	NR	NR	NR	0.501	0.523	-4.1
	CW	NR	NR	NR	0.832	0.865	-3.8
W11	CCW	NR	NR	R	0.437	0.447	-2.3
	CW	NR	R	R	0.808	0.856	-5.6
W12	CCW	NR	NR	R	0.634	0.299	-112.0
	CW	NR	R	NR	1.000	0.472	111.7
W13	CCW	R	NR	NR	0.448	0.298	50.2
	CW	R	NR	NR	0.953	1.000	-4.7

Location	LC	KW-2	KW-3	KW-14	KW-8	KW-7	Strains with Redundancy	Strains without Redundancy	% Change
W1	CCW	R	NR	R	NR	NR	0.711	0.378	87.8
	CW	R	R	NR	R	NR	0.971	0.384	152.7
W2	CCW	R	NR	R	NR	NR	0.527	0.331	59.2
	CW	NR	R	R	R	R	0.246	0.172	42.7
W3	CCW	NR	R	NR	NR	NR	0.731	0.605	20.9
	CW	R	NR	R	R	NR	1.000	0.603	65.7
W4	CCW	NR	R	R	NR	R	0.892	1.000	-10.8
	CW	NR	R	R	R	NR	0.649	0.729	-10.9
W5	CCW	NR	NR	R	R	NR	0.255	0.271	-5.7
	CW	NR	NR	R	NR	NR	0.333	0.392	-14.8
W6	CCW	R	R	NR	R	R	0.489	0.524	-6.7
	CW	R	R	NR	R	NR	0.579	0.607	-4.6
W7	CCW	R	NR	NR	R	R	0.213	0.179	18.5
	CW	R	R	R	NR	R	0.358	0.265	35.1
W8	CCW	R	R	R	NR	NR	0.381	0.231	64.9
	CW	R	NR	NR	NR	R	0.515	0.347	48.6
W14	CCW	R	R	NR	R	NR	0.193	0.186	4.1
	CW	R	R	NR	NR	NR	0.284	0.285	-0.4

Worst weld noncompliance combinations for rear welds (top) and front welds (bottom). R represent redundancy and NR is non-redundancy.