Graphics

Design Refinement by Iterative Virtual Experimentation (DRIVE) for Analysis of Steering Column Mounting Bracket Design of an On-Highway Construction Vehicle

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Introduction

In designing componentry for industrial equipment, it is often necessary to theorize and design many versions of a system and/or components. While there exist applications where Finite Element Analysis (FEA) is utilized along with Computer-Aided Design (CAD) to produce design optimizations, there are very few applications where CAD and FEA are combined with experimental designs or design of experiments (DOE). By combining experimental design methods with commonly used analysis and design tools such as CAD and FEA, designers can develop powerful statistical models and utilize graphics visualization to analyze various design iterations. Such an integrated approach can result in a more robust and optimized system design. Not only does this help improve overall system performance but also has the potential to significantly reduce the cumulative time and cost spent on designing the system. This paper proposes the DRIVE (Design Refinement by Iterative Virtual Experimentation) methodology that integrates DOE with traditional CAD and FEA tools in a concurrent manner. With the utilization of the DRIVE methodology, the total number of design possibilities that can be initially explored will increase significantly and, thus, lead to an overall more robust and functional final design. Another benefit of the DRIVE methodology is that this integrated approach can help save countless hours of physical modeling, mock-ups and prototype manufacturing as well as eliminating unnecessary waste and scrap materials that would be associated with the testing of prototype components.

DRIVE Methodology Components

To better understand the working of the DRIVE methodology, let us first explore its three basic components: CAD, FEA, and DOE.

The Fundamentals of Design (CAD)

Design is formulation of a plan that satisfies a specific need or simply solving a problem. During the design process, the designer must ensure that the design meets certain predetermined criteria. The product must be functional, as well as reliable, safe, usable, manufacturable and marketable, among other things (Budynas et al., 2008). Design is an iterative as well as innovative process (Earle, 2000). It is also a decision-making process. All too often designers find themselves faced with decisions that must be made with either too little information, sometimes with just the correct amount of information, and sometimes with an abundance of information that partially contradicts itself. These decisions must sometimes be made tentatively, with a reservation to change at a later time as more information becomes available. Designer must be comfortable with this decision making and problem solving process. Various analysis tools from mathematics, statistics, computing, and graphics fields can be combined to formulate a plan that yields a product with desirable characteristics. Nowadays, CAD modeling is extensively used by engineering designers to assist in the overall design process.

Finite Element Analysis (FEA)

Finite element analysis (FEA) is a procedure utilized in engineering as an approximation to the solutions of boundary value problems. In a typical boundary value problem, one or more variables satisfy a differential equation within known boundaries. Depending on the problem that is being solved, these variables can include displacement, temperature or many other parameters (Hutton, 2004). While basic methods of mechanics can be used to analyze simple geometrically shaped components, analyzing more complex components is challenging. Methods of approximation that are less representative than their simple counterparts are used in such cases. By dividing the structure of any complex component into small, finite elements, we are able to closely approximate the true geometry of the component. As the number of elements increases and their corresponding size decreases, we get better approximation of the geometry of the actual component. Use of powerful FEA software with efficient and accurate solver routines brings a general ease to the preprocessing stage of the analysis that includes the building of the model and creating the mesh. The FEA software also aids in the post-processing stage of reviewing the calculated solution results (Budynas et al., 2008).

Experimental Designs (DOE)

The last part of the engineering analysis assemblage in this research involves experimental designs or design of experiments (DOE). Experiments are performed in nearly every field to discover some sort of information about a particular system or process. In its formal definition, an experiment is simply a test, or series of tests, in which deliberate changes are made to the inputs of a process or system for the express purpose of observing and analyzing the effects that those changes make on the output of the system being studied. It is apparent that experimentation plays a vital role in product realization, in which we find the activities of new product design and product improvement. The ultimate objective in these activities is usually to develop a component or system that is robust and receives minimal influences from outside sources of variability (Montgomery, 2012). Some of the more useful aspects of experimental designs in the engineering design process are:

- Validation of important product features that affect product performance.
- Comparison and evaluation of multiple design configurations.
- Determination of product features that yield robustness.
- Evaluation of alternative materials.

DRIVE Methodology and its Application to the Steering Column Mounting Bracket Design

This section outlines the DRIVE methodology and its application to the steering column mounting bracket design. The particular application of the component lies within the driver's cabin of an on-highway construction vehicle. A typical installation of a steering column sub-assembly contains several components that are installed as a complete unit within the driver's cabin. Figures 1 and 2 show the actual pictures taken of the driver's cabin entry point and the steering column bracket sub-assembly located within the cabin respectively. The main focus on the mounting bracket (shown in Figure 2) is centered on the premise that upon gaining entry to the driver's cabin, the driver will pull on the steering wheel to aid in entry to the cab. This results in a force and moment being encountered at the attachment point of the steering column and the mounting bracket.

Figure 1. Photo of the driver's cabin entry point

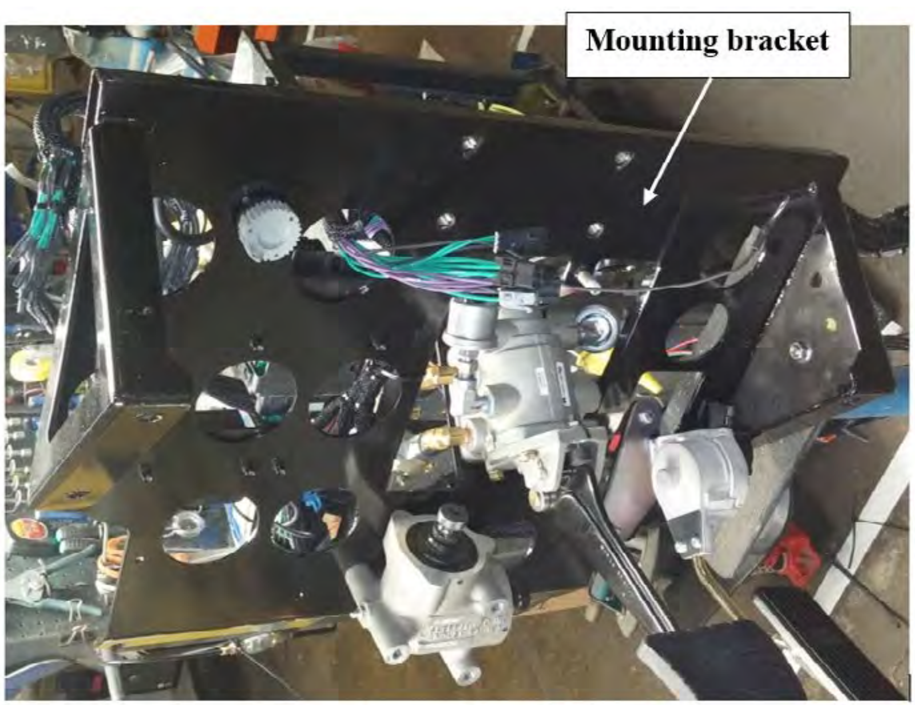

Figure 2. Actual steering column bracket sub-assembly

When an operator attempts to gain entry into the cabin, he or she will tend to grab the steering wheel and utilize it as a grab handle to aid the entry into the cabin. When this process is repeated over multiple ingress and egress cycles, there is an undue stress put upon the base mounting bracket, of which it is not intended to function as the mounting bracket for an impromptu grab handle.

In this case study we use the DRIVE methodology to examine the means by which we can reduce the maximum observed stress within the mounting bracket for a given load. Thus, the response/output variable selected for this multi-factorial experiment was the maximum observed Von Mises stress on the bracket measured in pounds per square inch (psi) units. The design features (factors) chosen to vary within the mounting bracket were: presence of flange radii, increased flange width, and presence of weight reduction holes (shown in Figure 3). Each factor is comprised of only two levels as shown in Table 1. Table 2 summarizes the factor-level combinations (treatments). Three design factors, each with two levels (present/not present) result in 8 unique design alternatives.

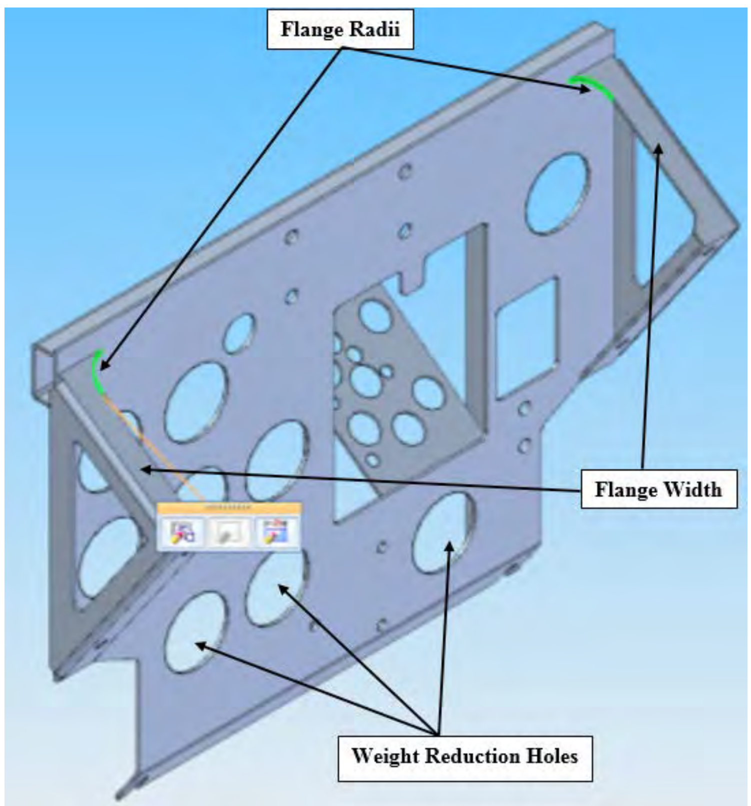

Figure 3. Three design features (factors) within the mounting bracket

Table 1. Summary of design factors and their levels

Design Factor		Levels	
		Low (-)	High (+)
Factor A:	Presence of flange radii	No	Yes
Factor B:	Increased flange width	No	Yes
Factor C:	Removal of weight reduction holes	No	Yes

Table 2. Factor level combinations (treatments)

Design Alternatives (Treatments)	Factors			Description
	A	B	C	
(1)	-	-	-	None
a	+	-	-	Presence of flange radii
b	-	+	-	Increased flange width
ab	+	+	-	Flange radii & increased flange width
c	-	-	+	Weight reduction holes removed
ac	+	-	+	Flange radii & weight reduction holes removed
bc	-	+	+	Increased flange width & weight reduction holes removed
abc	+	+	+	All factors present

Figure 4 shows the three basic phases of the DRIVE methodology. The first phase involves creating three dimensional CAD models of the driver's cabin and the steering column mounting bracket designs using a parametric CAD software package. These designs are based on actual cabin of the construction vehicle and the steering column bracket sub-assembly shown in Figures 1 and 2 respectively.

The second phase involves performing finite element analysis. First step in FEA was to apply boundary conditions and material to the CAD models developed in the first phase. Next, the external loads were applied to the model and simulations were performed.

The third phase involves performing analysis of variance (ANOVA) on the data obtained from the second phase. A 2^3 factorial design with two replicates was used to examine the influence of the three design factors on the maximum observed Von Mises stress within the mounting bracket.

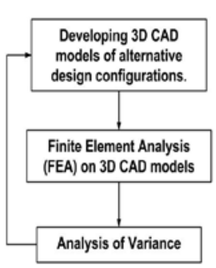

Figure 4. Three basic phases of the DRIVE methodology

Computer Aided Design

Figures 5 and 6 show the developed CAD models of the driver's cabin and the steering column bracket sub-assembly located within the cabin. The eight different combinations of the factor levels (design alternatives) and their associated CAD geometry representations are shown in Figure 7 in accordance with the standard design of a 2^3 experimental design as documented in Table 2. Each treatment was implicitly modeled within the CAD software.

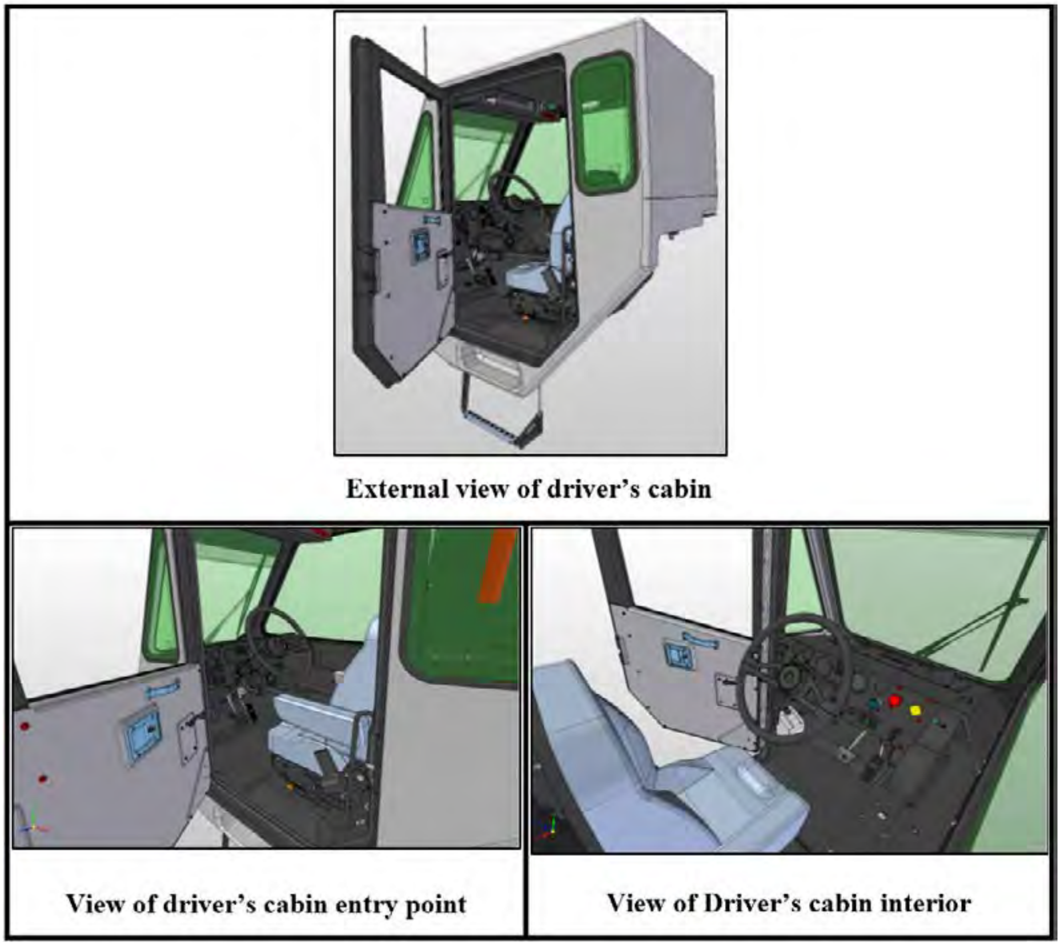

Figure 5. Developed CAD model of driver's cabin

	
Side view of steering column sub-assembly	Steering column sub-assembly with clear view of the mounting bracket

Figure 6. Steering column sub-assembly CAD model.

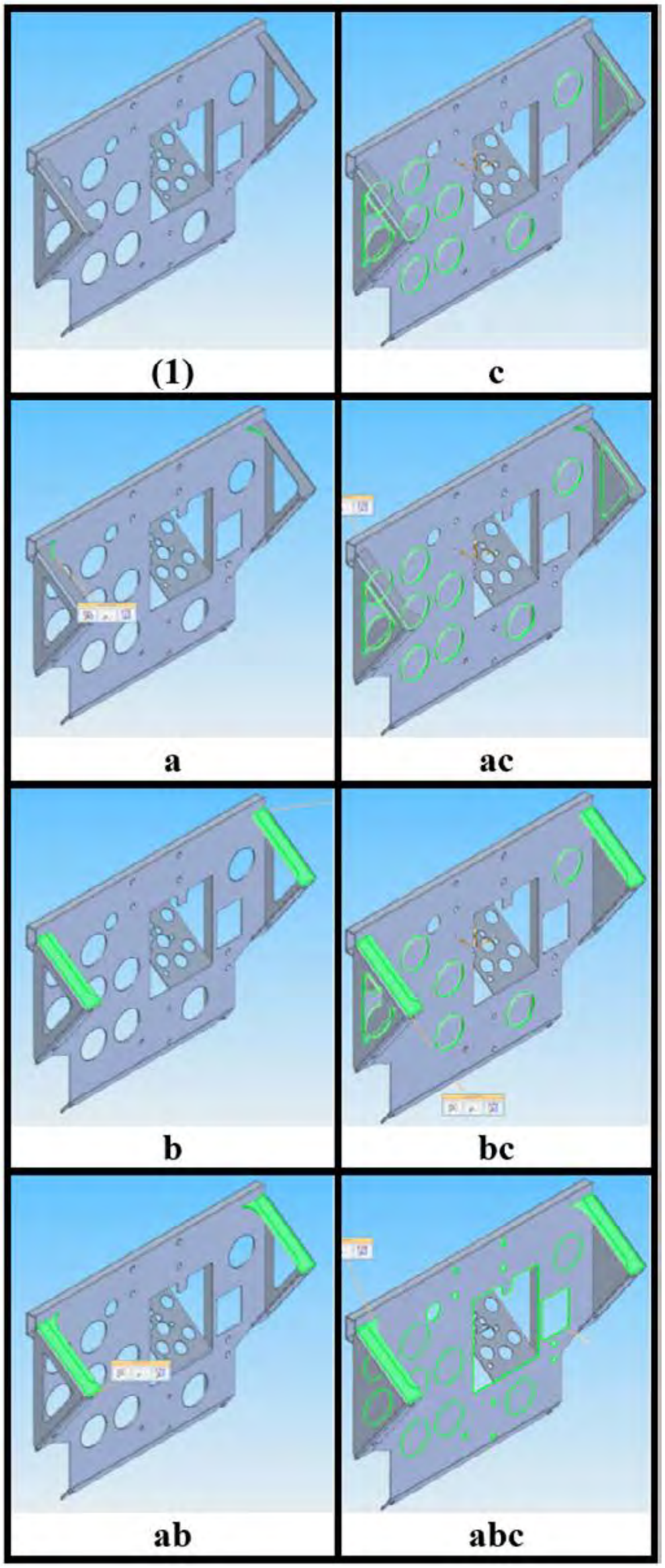

Figure 7. CAD models for 8 unique design alternatives of the mounting bracket

FEA Simulations on 3D CAD models

The selection of three design factors and two levels of each factor created 8 different scenarios for FEA as shown in Figure 7. As can be seen in Figure 5, the mounting bracket has a steering column attached to it. A maximum downward force of 500 lbf was applied to the steering column in order to simulate real life loading conditions. Two replicates were used in the experiment with subjective mesh size factors of 8 and 9 in the simulation software. This effectively introduced a type of virtual noise into the experiment so that we can adequately study the effect of the different treatments on the response variable and optimize the relevant design.

Data were collected on the completed FEA analyses and the subsequent maximum observed stress within the mounting bracket and the factor of safety was recorded for each replicate of each treatment (design alternative) in the experiment. These data are catalogued in Table 3. Figure 8 depicts example FEA simulation results (Von Mises stress diagrams) for the eight design alternatives at mesh size factor of 8. A scale is also provided with units in the kilo-pound per square inch (ksi).

Table 3. Maximum stress observed and factor of safety

Run #	A	B	C	Treatment	Maximum stress (psi)		Factor of Safety	
					Replicate 1	Replicate 2	Replicate 1	Replicate 2
1	-	-	-	(1)	23,700	32,000	1.60	1.19
2	+	-	-	a	17,600	18,500	2.16	2.05
3	-	+	-	b	22,800	25,200	1.67	1.51
4	+	+	-	ab	19,600	19,400	1.94	1.96
5	-	-	+	c	23,600	26,100	1.61	1.45
6	+	-	+	ac	17,800	17,900	2.13	2.13
7	-	+	+	bc	23,300	27,800	1.63	1.37
8	+	+	+	abc	19,300	19,100	1.97	1.99

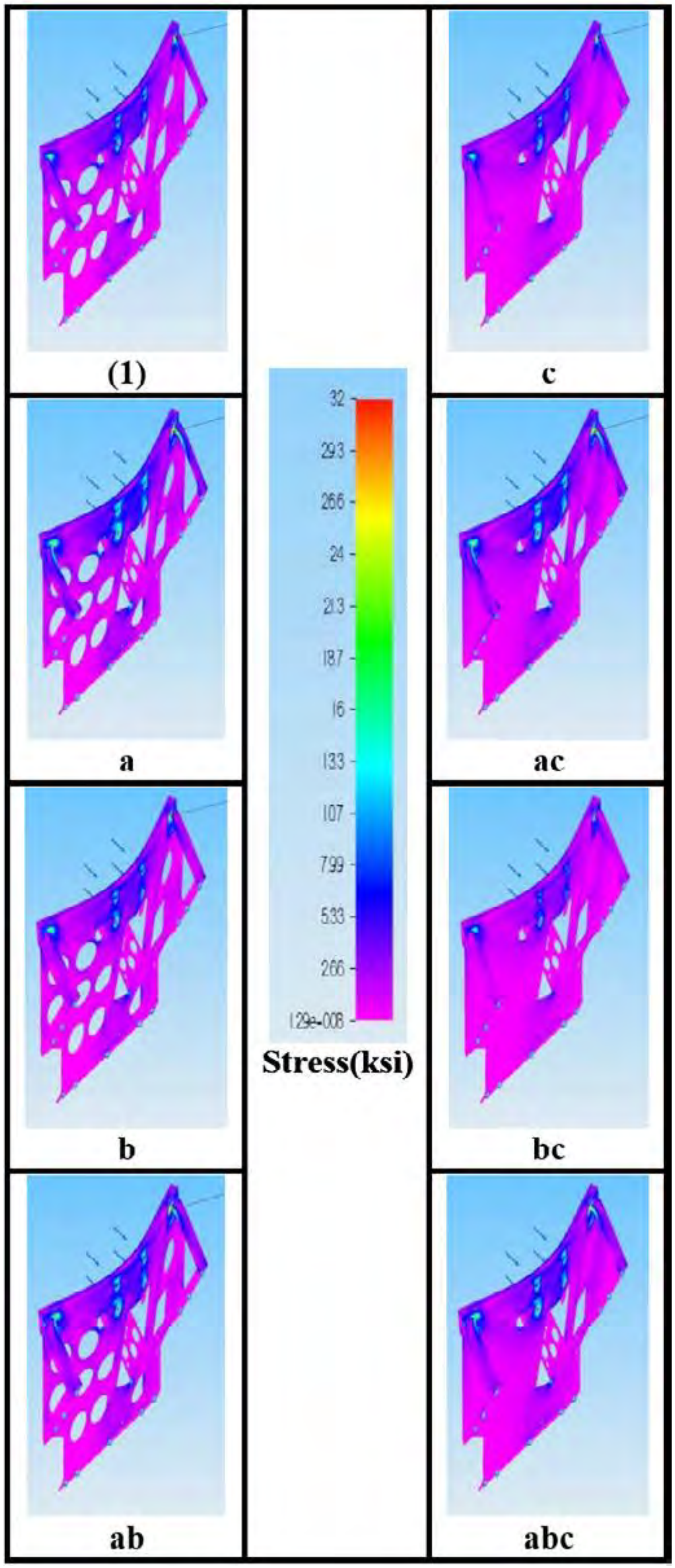

Figure 8. FEA simulation results (Size 8 mesh)

Statistical analysis was performed utilizing Minitab statistical software. The input worksheet was configured for the 2^3 factorial design with two replicates. The data obtained for the maximum observed stress (Table 3) were entered into the worksheet and then the factorial design was analyzed at confidence level of 99% ($\alpha = 0.01$). Table 4 shows the ANOVA output. The *P* value from the ANOVA output is used to determine the significant design factors and interactions. From Table 4, it is clear that only factor that has significant impact on the maximum observed stress within the mounting bracket is factor A, "the presence of the flange radi**i**", since the associated *P* value is less than α value of 0.01. The same conclusion can be drawn from the main effects plot (Figure 9), which indicates that average observed maximum stress within the mounting bracket reduces drastically when flange radii are added to the design.

Table 4. Analysis of variance for maximum observed stress within the mounting bracket

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	211544375	30220625	4.74	0.022
Linear	3	192111875	64037292	10.04	0.004
Flange radius	1	191130625	191130625	29.97	0.001
Flange width	1	30625	30625	0.00	0.946
Holes removed	1	950625	950625	0.15	0.710
2-Way Interactions	3	14026875	4675625	0.73	0.561
Flange radius*Flange width	1	8850625	8850625	1.39	0.273
Flange radius*Holes removed	1	225625	225625	0.04	0.855
Flange width*Holes removed	1	4950625	4950625	0.78	0.404
3-Way Interactions	1	5405625	5405625	0.85	0.384
Flange radius*Flange width*Holes removed	1	5405625	5405625	0.85	0.384
Error	8	51025000	6378125		
Total	15	262569375			

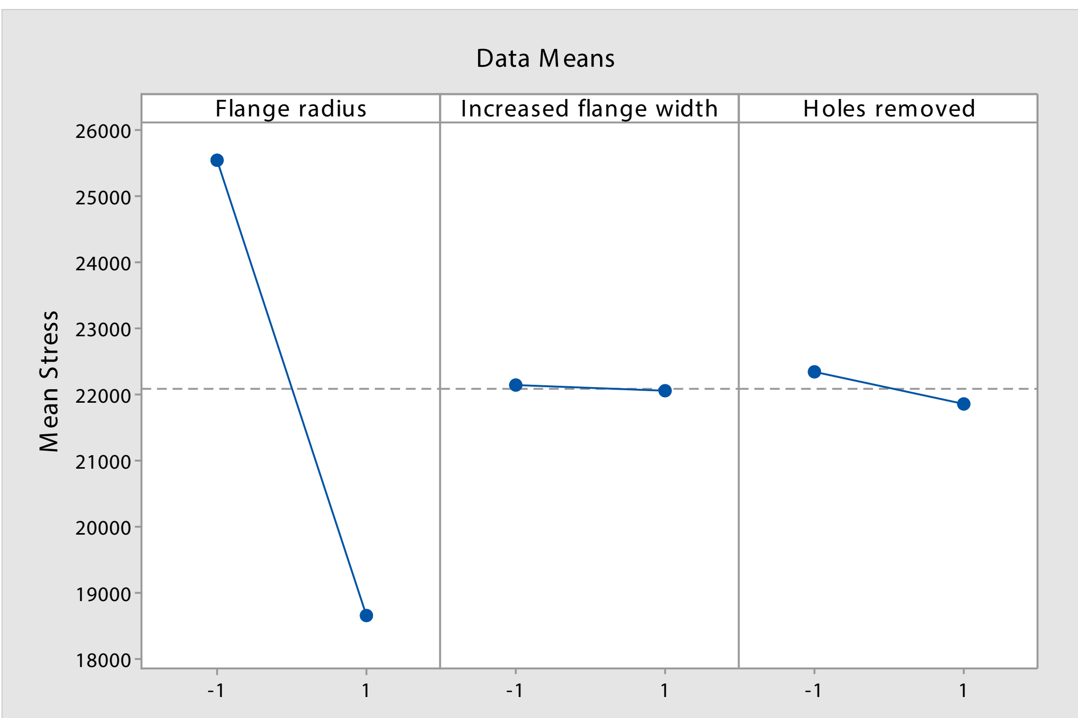

Figure 9. Main effects plot

The residuals from a factorial experiment play an important role in assessing model adequacy. Figure 10 shows four-in-one residuals plots for the experiment. The normal probability plot gives no indication of non-normality or possible outliers. The residuals versus the fitted values plot shows two large residuals towards the right end of the plot. This needs to be investigated further. The two other plots, histogram of residuals, and residuals versus order appear normal. So, based on these plots, the statistical model used appears to be adequate and the results of the experiments are valid.

Figure 11 shows the cube plot which helps in selecting appropriate levels of each of the significant design factors in order to optimize the design, one that will result in reducing the maximum observed stress within the mounting bracket. The cube plot confirms that the minimum stress can be observed when the flange radii are present, which is indicated by the values on the right side surface of the cube plot in Figure 11.

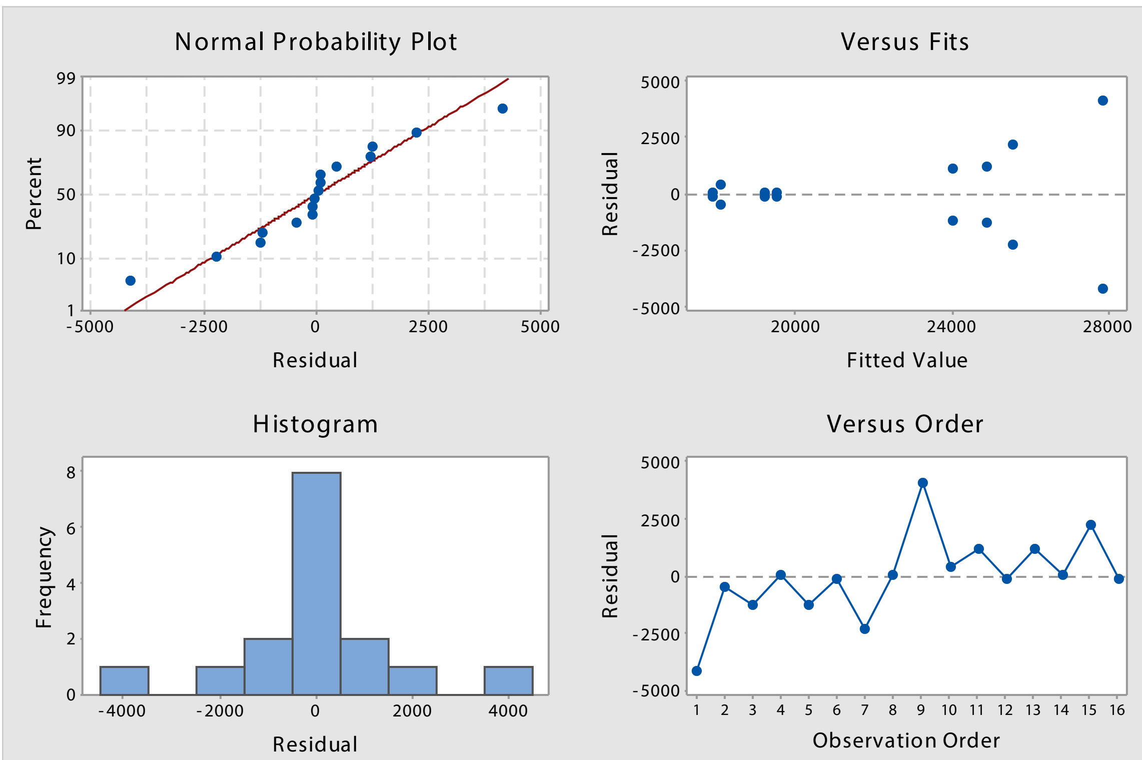

Figure 10. Four in one residual plots for maximum observed stress

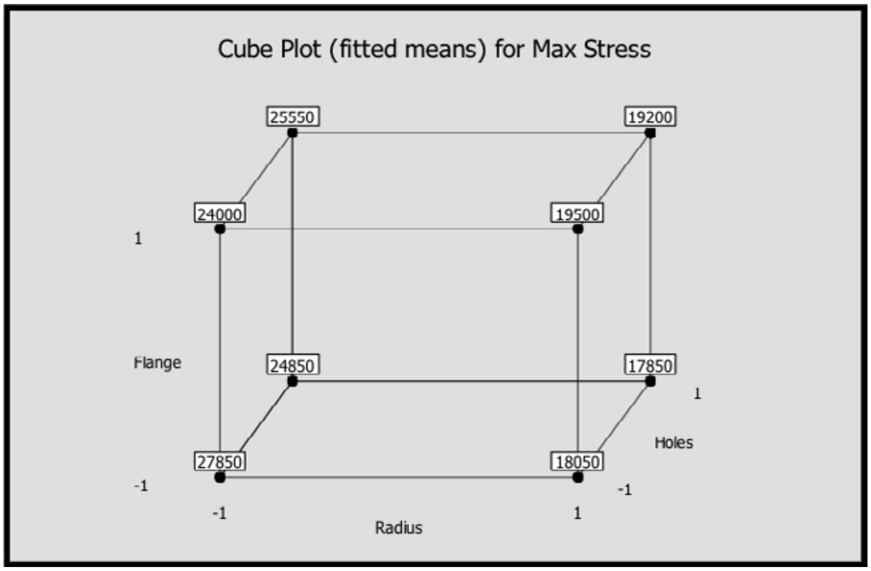

Figure 11. Cube plot for maximum observed stress

Summary

The DRIVE methodology discussed in this paper accomplished its objective of establishing optimal parameters for the design of the mounting bracket. The result suggests that the only factor that has statistically significant impact on design and guaranteed to improve the overall performance of the design is Factor A: the presence of flange radii. Thus, this would be the only feature that should be included in the further refinement of this design analysis. Further, the basic steps as outlined earlier, pose a generic empirical model that can be used for similar future design studies.

By incorporating the aspects of DOE, this work further extends the recent research efforts by May et al. (2012), Watson and Joshi (2012, 2013), whereby design simulations were combined with CAD modeling to address critical design issues. By synergistically integrating the elements of CAD, FEA, and DOE, we are now able to virtually create multiple potential designs and analyze those designs by simulating them within the virtual environment. In the past, we would have to rely on design tools that were very subjective, such as concept evaluations. This new approach enables us to generate hard data and statistical evidence that are both objective and definitive to aid in the decision making.

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