A Modeling Paradigm for Product Specific Design Analysis Integration

P K Saini¹

¹ Mechanical Engineering Department, National Institute of Technology, Kurukshetra, India
pk.saini@nitkkr.ac.in

Abstract. In spite of recent advancements in computer aided design and engineering (CAD/CAE), such as parametric geometry and automatic mesh generation, a large gap exists between computer based design model and analysis model. In this paper, a new product specific approach to integrate design and analysis integration is proposed. The primary objective of this approach is to capture designer’s intent from the limited interaction with the designer in a language that is familiar to designer and to provide the feedback on the suitability of the design based on the finite element analysis (FEA) so that the design is automatically and iteratively modified. Hence, the proposed modeling paradigm provides capabilities of analysis to the designer and acts as a black box without requiring the designer to possess relevant knowledge of FEA. Priority has been given to the class of problems termed as routine analysis – the regularly used, established analysis model in the product design. A representative case study pertaining to Belleville spring is discussed in the context of the proposed methodology to demonstrate that it enables highly automated routine analysis through FEA for the model.

1. Introduction

The rapid growth of CAD packages has led to a demand for better integration of CAD and FEA systems which have become the most common tools used in industries to assist in product development [1-5]. Dan Dietz [6] discusses the possibility of a ‘One-stop design and analysis’, wherein he explores the capabilities of software tools that are transgressing the boundaries set by traditional CAD/CAM/CAE programs. He discusses the improvements made in FEA codes and also the CAD packages during that period, but emphasizes that improvements in the links between design and analysis can have a significant impact on the cost of product. He also discusses a number of different codes that combine CAD and FEA. Further, he describes about the interpretation of FEA results made available via a unified CAD interface to engineers. This has been implemented in Rolls Royce Industrial Power Group, wherein, an ANSYS interface to its CADDS 5 CAD/CAM software is developed.

Similar approach to interface CAD and FEA has also been described by Brar et al [7] in their work for MacNeal-Schwendler Corporation (MSC). Their paper describes the various translation methods involved in interfacing of CAD programs such as AutoCAD to MSC’s structural finite element programs- MSC/NASTRAN, MSC/XL, MSC/pal2 and MSC/mod. Another paper from MSC by Bill Moffitt [8] provides an overview of such attempts on design-analysis integration.

Sahu and Grosse [9] in their paper discuss the integration of FEA results with CAD design models to support the progressive design modification. A successful compilation of design and analysis modules is ensured by integration of continuum-based numerical simulations into a computational system for the design of mechanical components. This technique of successive design modifications is one of the
early ones that require communication between the design and analysis domains and has been implemented in CSN-Designer (Cognitive Symbolic and Numerical Designer).

Lu et al [10] have also proposed a full integration of FEA simulation code within a CAD system. In their paper, they have discussed the design-analysis integration in sheet stamping applications. The numerical simulation is possible without leaving the CAD environment. A prototype system is then discussed in order to demonstrate the feasibility and advantages of such an approach.

Hence, it is apparent that design-analysis integration is a keenly pursued topic. Major research work is in progress at various institutions and organizations, such as, Georgia Tech. (Engineering Information System Lab) [11] and IBM [12] (as a solution for BMW motors), where the work is based on the CAx systems domain. The currently available solutions closely complying with the concept of design-analysis integration include CATIA [12] and Pro/ENGINEER. These packages have integrated many of the design and analysis functions, however, these generic software do not capture the designer’s intent and are not capable of creating analysis database. The philosophy of integration described in the present work is different since it is intended to make the process of analysis invisible to the designer. The available software may integrate CAD and FEM packages but do not ‘integrate’ the design-analysis procedures and hence, do not support ‘conceptual’ design methodology.

2. Methodology
Despite the advances made in the fields of CAD and CAE, a significant gap still exists between these two stages of product development cycle. In fact, an interactive and seamless link between computer aided geometric design (CAGD) and CAE is observed and identified as one of the unfulfilled promises of CAD. Due to the gap between CAD and CAE, as mentioned above, the designers are often hindered in their efforts to explore design alternatives and ensure product robustness. In order to bridge the existing gap between CAD and CAE, the methodology adopted in the proposed product specific design-analysis (PSDA) model consists of various modules as shown schematically in Fig. 1. The modules bounded by dotted line in Fig. 1 perform the functions which are invisible to the designer. The following subsections dwell upon the description of these modules.

2.1. Designer workbench
Designer Workbench receives the design data from the designer in a designer friendly language and stores it in a design data file in order to create a 3D model. This information may be in the form of boundary constraints, loading conditions, space limitations, economic and aesthetic constraints. The boundary constraints include the limitations imposed on the design due to supports or boundary field specifications. If the designer chooses to skip the specification of boundary conditions, the PSDA system operates on the default settings. Moreover, the PSDA system provides the flexibility of selecting a specific failure criterion to be used subsequently for deciding whether the design is safe or unsafe.

2.2. CAGD Tool-box
The designer creates the 3-D model using CAGD Tool-box. Some of the commercially available CAD tools popularly used in the area of solid modeling include AutoCAD, Autodesk123D, Pro/ENGINEER, SolidWorks and Solid Edge. The CAGD tool-box desirable in design analysis integration is the one which is widely used in the component manufacturing industry and provides enough flexibility in drawing-generation. Some of the tools listed above offer application development module for development of program and dialog control language to create human-computer interface. Another important function is to provide database interface module so as to enable CAD tool to access data tables from a relational data management system (RDMS). This module stores the necessary data in solid model based on neutral format (IGES/STEP) and supplies it to the next module [13].

2.3. Geometry/Topology Extractor
This module decodes the B-rep file generated by the CAGD tool-box to recognize the component features and extract the relevant geometric information in the form of vertices, edges and faces. In order to accomplish this task, a computer program is developed that reads the solid model file and
stores the necessary data in an abstracted model file to be used further by FEA Workbench. This requires knowledge of the specific kind of neutral format in which the solid model data file is created. For example, a STEP file consists of three types of data, namely, descriptive, geometric and topological. The structure of STEP is language based and is described by an ambiguous context free grammar to facilitate passing software. The grammar is expressed in wirth syntax notation. The information contained within the file is in free format and thus not column dependent. The file is organized in a modular manner and consists of several sections [14, 15].

**Figure 1. Product Specific Design-Analysis Model**

2.4 **FEA Workbench**

FEA Workbench utilizes three types of database along with the geometric information to create an analysis data file in a language usable by CAE tool. These three databases may be created by default or according to designer specifications stored in the design data file. These three databases include

a) **Material Properties**

Depending upon the application, material properties can be linear or nonlinear. The constant linear properties are further subdivided as isotropic, orthotropic and anisotropic. The nonlinear properties include plasticity data (stress-strain curves for different hardening laws), magnetic field data (B-H curves), creep data, swelling data, hyperelastic material data etc.

b) **Loading Conditions**

The information regarding loading conditions includes boundary conditions (constraints, supports or boundary field specifications) as well as other externally and internally applied loads. The loads are classified as: degree of freedom constraints, forces, surface loads, body loads, inertia loads and coupled-field loads.
c) Mesh Control
This controls the character and quality of the mesh by specifying the types and other information about the elements used in analysis. The types of element can be classified on the basis of discipline (structural, thermal, magnetic, electric) and dimension (1D, 2D and 3D).

2.5 CAE Solver
CAE Solver tools, such as, ANSYS, MCS/NASTRAN, ABAQUS and NISA utilize the model generated by FEA Workbench and analyze the designed component. In the present work, ANSYS is primarily used as the CAE Solver tool as it is one of most commonly available packages. ANSYS uses the model and loading information from the analysis data files and post processes the output data. The post processor of ANSYS has many capabilities, such as, display of contours and deformed shapes, tabular listings, error estimation, load case combination and calculations among results data.

2.6 Evaluator
The evaluator receives the result data generated by the CAE Solver tool and determines whether the design is safe or not. This is accomplished by using the failure criterion applicable in the particular case, as specified in the failure criteria database. For example, the von-misses stress is one of the most commonly used criteria to determine the onset of plastic deformation leading to final fracture of various mechanical components. Another failure criterion involves the determination of maximum deflection and its comparison with the preset allowable limit. In case the design passes the aforesaid failure test, it is further evaluated on the basis of other constraints specified by the designer, i.e., economic and space constraints. The design is rated as ‘safe’ if the above constraints are satisfied and this information is furnished to the designer, otherwise the control is shifted to the design data modifier.

2.7 Design Data Modifier
This module comes into execution in case the design fails, as determined by the evaluator on the basis of the results obtained from CAE Solver tool. It modifies the critical dimension in order that the design approaches towards being safe and transfers the control back to the FEA Workbench. Since the design data modifier changes the design data without any interaction with the designer by using its in-built decision making algorithms, therefore, the PSDA model works as an intelligent system.

3. Implementation
The proposed methodology, as described in Section 2, is applied for the case of Belleville spring with constant as well as linearly varying thickness. Belleville springs, as shown in Fig 2, are conical disks of rectangular radial section [7,16]. Normally with outside diameters (D₀) ranging from 8 to 250 mm, they can be axially loaded from 120 to 250,000 N with the maximum stress on the top inner edge.

![Figure 2. Schematic of a Belleville spring](image1)

![Figure 3. Belleville spring of variable thickness](image2)
A custom spring is obtained for each outside diameter \( (D_0) \) by varying the height to thickness ratio \( (h/t) \) and the \( D_0/D_1 \) ratio in a range from 1.2 to 5.0. The Belleville springs are designed to bear maximum loads with minimum strain, while keeping a large amount of energy in relation to the space they occupy. They can be compressed without being subjected to lasting strain or fracture. Since these springs are individually very rigid, they are usually arranged in parallel/series assemblies to get the desired elastic properties. Belleville springs have been used in a wide variety of applications including: recoil mechanisms for guns, spring washers to apply gasket pressure or to increase elasticity of bolted assemblies, clutches, pressure-relief valves, automatic transmissions, oil-seal resilient members, and buffer springs [17,18].

In order to facilitate easy understanding of the methodology, the case of a Belleville spring is considered. The first step involves the specifications of applied load and space constraints in terms of maximum \( D_0 \). The designer may also specify the failure criterion to be used subsequently. The designer then creates the geometry of Belleville spring by using ProE Wildfire in accordance with the guidelines for selecting the range of geometric parameters specified in RDMS. The Geometry/Topology Extractor (GTE) decodes the 3D-model stored in STEP format to yield \( D_0 \), \( D_1 \), \( h \) and \( t \) of Belleville spring. The mesh control function of the FEA Workbench selects SHELL51 element, as designated in ANSYS, which has four degrees of freedom at each node: translations in the nodal x, y, and z directions and a rotation about the nodal z-axis. These mesh specifications in conjunction with the dimensions given by GTE as well as material properties and loading conditions are used to create analysis data file. This is analyzed by ANSYS (CAE Solver) to give the result data. These FEM results are obtained for constant thickness \( (r = 0) \) and linearly varying thickness. Figure 3 shows salient dimensions of a Belleville spring with linearly varying thickness, where \( t_{cd} \) represents the particular case of constant thickness spring. The results obtained from PSDA model are compared with the corresponding analytical results, as shown in Fig 4 and Fig 5 for a Belleville spring. The analytical results are computed using the equations by Rosa et al [19] for the case of spring with linearly varying thickness. The thickness of spring is defined as:

\[
t(x) = T_0 + T_1 \times x
\]

(1)

where,

\[
T_0 = t_c \left[ 1 + \frac{a + b}{a - b} - \frac{2c}{a - b} \right], \quad T_1 = \frac{2t_c}{a - b} \quad \tau = \frac{t_a - t_b}{2t_c}
\]

where, \( t_c \) is the thickness at \( c = (a+b)/2 \), the tapering parameter \( \tau \), as defined above, reduces to zero for the case of constant thickness spring.

The load \( F \) is given by:

\[
F = \frac{2\pi E \phi}{a - b} \left( (\beta - \phi)(\beta - \phi/2) \left[ T_0 U_1 + T_1 U_2 \right] + \frac{1}{12} \left[ T_0^3 U_3 + 3T_0^2 T_1 U_4 + 3T_0 T_1^2 U_1 + T_1^3 U_2 \right] \right)
\]

(2)

where \( \phi \) is the angle of rotation angle, \( \beta \) is the angle of spring, and

\[
U_1 = \frac{1}{2} \left( l_1^3 - l_2^3 \right) + c(l_1 - l_2) + c^2 \ln \frac{a}{b}, \quad U_2 = \frac{1}{3} \left( l_1^3 - l_2^3 \right) + \frac{c}{2} \left( l_1^2 - l_2^2 \right) + c^2 (l_1 - l_2) + c^3 \ln \frac{a}{b}
\]

\[
U_3 = \ln \frac{a}{b}, \quad U_4 = l_1 - l_2 + c \ln \frac{a}{b}, \quad l_1 = c - a, \quad l_2 = c - b,
\]

\[
c = \frac{(a - b)^2}{-2\tau(a - b) + (a - b) \ln \frac{a}{b} + \tau(a + b) \ln \frac{a}{b}}
\]

(3)

The load \( F_0 \) required to flattened the spring completely is obtained by substituting \( \phi = \beta \) in equation 2. Hence,
The circumferential stress is given by:

\[
\sigma_r(x, y) = \frac{E \phi}{c - x} \left[ x(\beta - \phi/2) + y \right], \quad (l_1 < x < l_2)
\]

and

\[-t(x)/2 < y < t(x)/2\]

The circumferential stress is given by:

\[
F_0 = \frac{\pi E \beta T_0^3 U_3}{6(a - b)}
\]
The load-deflection and stress-deflection curves shown in Fig. 4(a) and (b), respectively, are obtained for the case of constant thickness spring at four representative values of \( h/t \) ratio (0.7, 1, 1.3 and 1.5) within the practically used range, as specified by Wahl [17]. For the case of linearly varying thickness, Fig. 5(a) and (b) show the load-deflection characteristics and Fig. 5(c) and (d) show the stress-deflection characteristics at various values of tapering parameter (\( \tau \)) within the permissible range (\( |\tau| \leq 1 \)) specified by Rosa et al [19]. It is evident from Fig 4 and Fig 5 that the result obtained from CAE Solver using the proposed PSDA model are in close agreement with the analytical results. The evaluator rates the design as ‘safe’ if the following two conditions are satisfied simultaneously: (i) \( s \leq .75h \), and (ii) \( \sigma_{\text{max}} \leq \sigma_{\text{allowable}} \). In case the design fails, the design data modifier changes the \( h/t \) ratio for the case of constant thickness and \( \tau \) for the case of variable thickness or selects a different material.

4. Conclusions
The methodology adopted to accomplish the task of design-analysis integration is described in detail and its implementation is demonstrated for the case of Belleville spring with constant as well as linearly varying thickness. The results are summarized as follows:

- The main advantage of this scheme is that it combines two different stages of product development cycle, i.e., design and analysis in a single operation. This ultimately results in the minimization of total time consumed in product development by providing the product specific analysis capabilities at the design stage itself.
- The proposed modeling paradigm reduces the strain on the product designer to have an understanding of analysis techniques.
- It needs a mention that the approach used in the present work is not generic as it is limited to a specific product only. An effort directed towards the development of generic CAD-CAE integration has a bright scope for further research in this area.

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