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ScienceDirect

Procedia CIRP 50 (2016) 58 – 64

www.elsevier.com/locate/procedia

26th CIRP Design Conference

A design methodology to support the optimization of steel structures

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Abstract

Steel constructions are widely used in several applications such as structures for buildings, stores, factories, and power plants. The scope of the research is to study a methodology to reduce the weight and the cost related to big frame steel structures during the early design phase, which is the phase where most of the project layout is defined. The main aim of this paper is the development of a platform-tool to support the automatic optimization of a steel structure using virtual prototyping tools and genetic algorithms. The focus is on the design of heavy steel structures for oil & gas power plants. This work describes in detail the design methodology and estimates the weight saving related to the re-design process of a test case structure. The design cases considered in the paper are those relevant to the operating.

Peer-review under responsibility of the organizing committee of the 26th CIRP Design Conference

Keywords: Design methodology; steel structures; oil & gas; optimization; simulations; genetic algorithms;

1. Introduction

A lot of research concerning the design optimization of steel structures is drawn in literature with the focus on cost reduction and weight optimization [1, 2, 3]. Indeed, the scope of steel structures regards several application fields such as civil buildings, bridges, factories, stores, and power plants. Typical onshore and offshore oil & gas constructions are steel structures with horizontal and vertical beams and decks. Many examples of oil & gas steel structures, called modules (Fig. 1), are used in power generation plants and also in upstream and downstream activities. In particular, the oil & gas markets have an ever growing demand for “plug-and-play” onshore and offshore solutions to mitigate issues that may interfere with smooth construction operations at the final installation site. Typically, those plug & play solutions are achieved through the modularization of functionally independent parts of a plant. Such modules are constructed and tested in a “controlled” environment and then transported to the final destination minimizing the site works and the risks for the customer. Based on this, gas compression and power generation modules can range from simple configurations to large modules that include both turbo compression and gas processing equipment in the same prefabricated structure. The average steel structure self-weight may raise over 600 tons per module. Due to their typical functionality the modules are subjected to static loads, dynamic loads, land transport loads, sea transport and fatigue loads. The weight optimization of steel constructions is a very important issue in the field of the oil & gas industry. In fact, the cost of a steel module is related to the structure’s self-weight, the number of beams, the types of beam sections, the number of overstressed beams and the type of construction. Simulation tools based on FEM analysis are used in the design of big steel structures due to the possibility to investigate the behavior of mechanical structures with virtual prototypes. Simulations with optimization analysis are proposed in many research activities in order to achieve the absolute maximum or minimum values of predefined objective functions [4]. One of the most famous types of the optimization procedures is the solution through genetic algorithms. In particular, genetic algorithms are proposed in a large number of optimization studies for different purposes [5]. The following sections describes the research background regarding the structural optimization paying attention to mathematical algorithms and solution procedures used in literature. Some background research

Peer-review under responsibility of the organizing committee of the 26th CIRP Design Conference
doi:10.1016/j.procir.2016.05.030

proposes a design optimization methodology [5], however the design of oil & gas structures requires a more complex and dedicated approach for different reasons. In fact, many researchers propose the optimization analysis of simple structures without a parallel analysis of load conditions. Many test cases of structures regard simple trusses [4] or portals [2] and the considered analysis are focused on static or at least dynamic loading. In addition, past projects do not consider the interaction between the design methodology and the work of the engineer in order to reduce the design time. Whilst, the intent of the method proposed in this paper is to define a reusable methodology to support the design optimization of big steel structures with attention to design time and different loading cases. The application of this approach at the early design phase could be very suitable to achieve a better project of mass reduction in the next executive phase with money saving benefits. A platform-tool has been developed to support the automatic optimization of steel frames using genetic algorithms. A test case is proposed to investigate the re-design of a lightweight module analyzing different solutions of steel beam grouping. The test is limited to the following load cases: static, sea transport, and land transport. The structure in subset is a typical power generation module with a heavy duty gas turbine (GT > 80 MW). The module is equipped with HVAC systems, bridge cranes, etc.

Nomenclature

DOE	Design Of Experiments
EHS	Environmental, Health, and Safety
FEM	Finite Element Analysis
GA	Genetic Algorithm
GT	Gas Turbine
HVAC	Heating, Ventilation & Air Conditioning
MOO	Multi-Objective Optimization
RSM	Response Surface Methodology

2. Background research

In this section, a selection of more interesting research projects about steel trusses is proposed in order to give a background of the research already performed and to describe better the context and the purposes of our work. As cited before, many research projects are focused on the weight optimization of basic and educational steel structures while other ones regard the study of more complex trusses. Concerning civil structures, the optimization analysis is sometimes also applied to composite structures like decks and complex shapes as roofs.

The genetic algorithms are considered as the most appropriate optimization method for the design of beam structures. This choice is due to the simplicity of the mathematical formulation, the independence from objective function, the possibility to work with discrete variables [5]. Prendes Gero et al. defined a mathematical elitist approach in order to increase the efficiency of the genetic algorithm method [5]. They analyzed two of the most common 3D structures: a portal frame structure and a three-floor steel building. The external loading conditions were combinations of wind and snow. This study began with a database of 2835 elements containing all the sections from the Spanish Basic Building Code, but subsequently they reduced to 114 codes of beam sections in order to limit the computational cost. They divided the structures in groups of beams taking into account loads applied and location. They found that the first structure, which initiates the optimization process, is extremely important for the development of the solution process while the number of groups influenced the computational cost. The results of simulations demonstrate that with more groups of beams the weight was reduced for all structures analyzed. They obtained a 9% weight reduction considering two objective functions: weight and penalty factor. The optimization of portal frames was also studied by McKinstray et all [2] that studied asymmetric portal frames for application as photovoltaic panels. In this case, the considered loading types were combination of snow and wind as viewed in the previous case. The objective function was the overall design optimization by GA with the minimum weight of beams and in accordance with the design requirements. Their approach led to weight savings of up to 40% [2].

GA are an example of applications of population-based evolutionary optimization methods, which are very common in science and engineering. Other examples are ACP (ant colony optimization), PSO (particle swarm optimization) and TLBO (teaching–learning-based optimization) which uses simple models of teaching and learning within a classroom as the basis for an evolutionary optimization algorithm. Farshchin et al. proposed a robust multi-class TLBO approach to optimize planar trusses up to 200 bars involved [6]. Each calculation iteration ended when a weight reduction of 4.5% was achieved. Türker et al. studied the dynamic behavior of a two-story structure using simulations based on FEM analysis [4]. They investigated the modal testing with and without braces. One of their remarks was that brace elements cause an increase in the natural frequencies because of the increased stiffening of the structures [4].

The optimization of transmission line towers focusing on industrial applications was proposed by Souza et al. through an approach based on topology optimization considering different pre-established template topologies [1]. Kociecki et al. proposed a two-phase genetic algorithm for size optimization of free-form steel space-frame roof structures [7]. They considered wind, snow and seismic loadings in linear structural simulations. The converge conditions allowed no more than 5% of overstressed beams. The achieved results provide a weight reduction of 12% using an automated design process.

Sharafi et al. studied a method for the shape and sizing optimization applied to steel sections using the graph theory and ACO algorithm [8]. They pursued a multi-objective analysis focused on optimum mass and strength. The used graph theory approach was very suitable for optimum shape analysis because the graph algorithms are good to find the shortest paths solution. In fact, since the thickness of the beam cross-section is uniform and constant, the mass minimization of the section reduces the issue to the length minimization of the section. Kaveh et al. provided a cost optimization study focused on a composite floor using a harmony search algorithm [3]. This algorithm imitates the musical