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Finite element method for optimum design selection of carport structures under multiple load cases

Özkal, F.M.[a,*], **Cakir, F.**[b,c], **Arkun, A.K.**[d]

[a]Erzincan University, Department of Civil Engineering, Erzincan, Turkey
[b]Yıldız Technical University, Department of Architecture, İstanbul, Turkey
[c]University of California, Pacific Earthquake Engineering Research Center (PEER), Berkeley, California, USA
[d]Amasya University, Department of Urban Design and Landscape Architecture, Amasya, Turkey

A B S T R A C T

In the field of structural modelling, it is obvious that the number of applicable designs for a particular structural necessity is limitless. Along with the integration of various kinds of available structural materials into this complexity, it gets harder to be able to determine the best design before the production stage. In recent years, with the improvement of computational and structural technology, there have been many studies on the optimal design selection. This study focuses on carport structures and pursuing their best producible shape. For this aim, a performance index formulation was developed to assist the decision of material efficiency as well as structural rigidity. Thereafter, five conceptual models were numerically modelled and finite element analyses (FEA) for multiple load cases were carried out. Reviewing the FEA results, the most appropriate model was determined by the application of this performance qualification method. Results of the analyses show that optimum design of structures under multiple load cases can be determined using finite element method.

A R T I C L E   I N F O

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**Corresponding author:*
fmozkal@erzincan.edu.tr
(Özkal, F.M.)

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1. Introduction

Structures can be designed in many different ways to provide the structural requirements such as performance, economy and appearance. The convenient design of structures is a very important factor for their structural performance. Shape of the structures is a very important factor for their structural behaviour. A poor design might cause fault and quality problems in a structure. It may conduce to decrease quality, performance and to increase cost and unnecessary material usage. Therefore, structural design is a major concern in engineering structures.

Design objectives are generally imprecise real-life situations as well as structural problems and natural idea is to deal directly with these ambiguous objectives. Hence, business experience shows that in many cases, it is beneficial to specify them crispy and then solve the optimization problem [1]. Design of structures depends on not only structural problems, but also knowledge and creativity of the designer. Therefore, design concepts can technically be discussed for a structure and designers seek the best feasible design. However, it is quite difficult to determine which of the designs is more efficient and better than the other ones. In recent years, with improvements of computer and structural technology, one of the ways to achieve an efficient structural design has been mathematical design optimization. Main goal of design optimization is to determine the best producible design for a structure under various constraints. Recently, design optimization with the finite element method (FEM) has become more popular with significant advances in computer technology. Today many designer and engineers appeal to finite element method and many structural analysis software packages are suitable for FEA.

The design process can be categorized in various ways, but in general, it consists of four main phases [2]. The first stage is to determine the functionality requirements and essential parameters; the second stage is to develop concept models; the third stage is to perform optimization on the developed concept models and the last stage is to compare the optimization results and decide the most suitable design before production. The general flow diagram of the structural design process is shown in Fig. 1. In this study, the best design of carport structures was determined by means of these four steps.

In previous studies, many researchers have investigated the design process and design optimization of many different structures [3-8]. In almost all of the past studies, urban structures have not been completely investigated. Therefore, this study focuses on the carport structures and their best producible design, since they are one of the most common urban structures. The study contributes to the best design of carport structures under multiple load cases in that it develops a performance index formulation, reveals the impact of material efficiency and structural rigidity on the best design. Moreover, this study helps to devise implement strategies and develop actions to improve best design. It is also indicated that the effective optimum design selection contributes to improve efficient structural design.

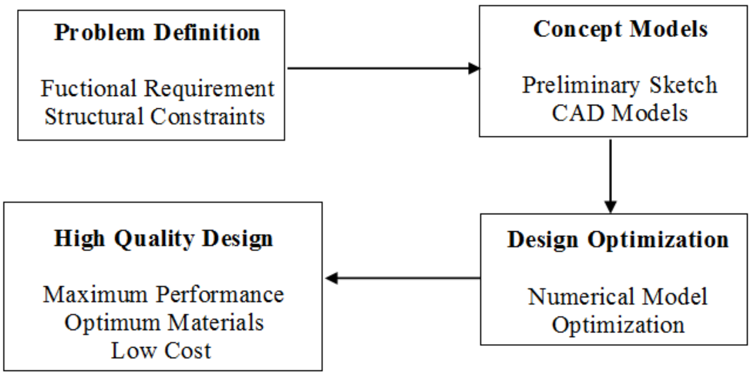


Fig. 1 Flow diagram of the structural design process

2. Carport structures

Carport structures, which are also known as car shelters, parking shades and parking structures, are open sided structures that usually consist of a roof and load bearing parts. Carports are popular all around the world and they are widely used at houses, office buildings, public areas, shopping malls, retail operations and shopping malls. Carports bring many great benefits, such as preventing damage from hailstones, snow and rain, minimizing sun damage, protecting against poorer weather, moisture and corrosion. Carports, which can be freestanding or attached to a building, may have a roofed or canopied form and sides of carports are left wholly or partially open. In other words, carports can be defined as a semi-open space in the context of architecture or space design.

The entrance of a carport is in contrast to a generally open garage. A common variant of the roofing is a corrugated sheet, trapezoidal or their transparent forms corrugated light panels or trapezoidal plates. Open carports without a roof are usually used as an optical setting of outdoor spaces to emphasize this by surrounding open spaces. Increasingly, free areas of the roof are also used for solar systems and as an extensive green roof. A green roof can contribute to decrease temperatures and reduce the heat island effect in the urban environment.

Furthermore, using carports, less materials are needed and the construction time is shorter than garage construction. Carports are assumed to be greener. Moore [9] lists the advantages of carports as serving as a covered main entrance and a place to entertain and do outdoor activities, in addition to the providing protection and storage for the cars. He also mentions that carports reduce complexity providing more than sufficient shelter, necessitate less construction materials, and accommodate as aesthetically architectural design. Conclusively, he states that people consider the environmental impact of garages compared to carports and choose the cost effective carports due to the rising environmental concerns. These several advantages contribute to widespread use of carports. On the other hand, carports offer no privacy, protection against theft or vandalism. A garage is more secure than a carport.

2.1 Historical background of carport structures

Car ownership has increased very quickly over the past forty years. This increase creates parking space need. Besides open space parking areas, carports which are semi open spaces were emerged especially in a single-detached dwelling setting. Gebhard proposes the older form of the porte cochère as the predecessor for the carports since it serves similarly to carport in terms of sheltering passengers as they exited carriages or automobiles. Gebhard [10] also stated that the architect Walter Burley Griffin used carports in the Sloan House in Elmhurst, Illinois in the early 1900s. By 1913, several Prairie School architects such as the Minneapolis firm of Purcell, Feick&Elmslie also used carports in a home at Lockwood Lake, Wisconsin. According to Fox and Jeffery [11], the expression "carport" was proposed by David Gebhard, an architectural historian, for the way that the term was begun from the component's utilization in 1930s streamline present day structures. Robinson [12] notes that carports were used by American famous architect Frank Lloyd Wright in Usonian Houses design in the 1940s. These carport structures are demonstrated in Fig. 2.

Moreover, Fox and Jeffery [11] points out that carports were accepted as an alternative to garages because of their cost and easy construction after Second World War. According to Moore [9], in the 19th century carports became typical design element of single-family residences and hotels. Today a vast range of sizes and designs of carports are available.

Fig. 2 Porte Cochère (a), Sloan House (b), Usonian (c) [13-15]

2.2 Structural failures of carport structures

Carport structures are exposed to many different external and internal effects throughout their lives. Therefore, a carport structure should be designed to withstand structural loading scenarios. Hence, the accurate estimation of the loads and their combinations on a carport might be the most important and the most difficult task for designers. Loads on carport structures are based on different types and forces, which are dead loads, live loads and lateral loads. Carport structures address the carrying problems of these loads.

Although carport structures are highly durable, some of them in the world unfortunately are deteriorated, damaged, collapsed or failed due to different effects. In general, these structures are destroyed and lost their qualities due to many reasons such as environmental conditions and natural disasters. Therefore, it causes irreversible negative effects on the structure. Observed structural failures occurs generally due to the material degradations and poor design. In the past, several carport problems arose because of poor design. If a carport is not well designed, successfully analysed and well-constructed; it may face some problems like collapse, deformation, fracture, fatigue, cracking or failure of fixtures, fittings or partitions and discomfort for occupants. Many carport structures are exposed to destructive vertical loads such as dead load and snow loads, and these loading scenarios can cause damages to the carports (Figs. 3a, 3b). This type of damage is very dangerous since it may cause fatal and destructive crashes and fractures, also causes diversified displacement of the carport components. Therefore, damage risk should be considered and some precautions should be taken against it.

In addition to vertical loads, lateral loads such as earthquake and wind loads may also affect the carports. Lateral loads generally cause to the lateral displacement and irrevocable damage. Wind loads lead to failure of the carport roof and affect the structural stability (Fig. 3c). Moreover, many carport structures are exposed to destructive earthquakes and these earthquakes cause some damages to the structure. Earthquake based damages occur especially on the vertical bearing components of the carport such as cracking and disintegration of the structure (Fig. 3d).

Fig. 3 Structural failure of carport structures due to snow load – (a) and (b), wind load (c), earthquake (d) [16-19]

3. Concept designs

The second part of the design process is to develop conceptual models. In this stage, designer selects the initial forms, type of structures and materials in terms of required structural function. Success at this stage depends on the ability, creativity and engineering approach of designers.

3.1 Material properties

Structural performance and behaviour of a structure technically depend on the construction materials. Moreover, the cost, quality, and design of a structure vary by selected materials. Therefore, selection of the appropriate material type is a crucial and vital process for engineering structures. Today, thousands of materials can be used for the all types of structures. However, not every material may be a correct choice for a structure; therefore, it is very important to select suitable materials.

Carport structures are generally made of steel, wood, plastic and composites. Because of proven properties and significant advantages, steel has been the dominating material for the load bearing parts of structures. Moreover, polymers are widely used for non-bearing parts of structures due to their lightweight, availability, easy usability and corrosion resistance. In this study, load-bearing parts of the carports were designed as structural steel and roofs as polyethylene. Materials properties can be obtained from ANSYS library [20], which are summarized in Table 1.

Table 1 Mechanical properties of the carport materials

Structural materials	Young's modulus (MPa)	Bulk modulus (MPa)	Shear modulus (MPa)	Poisson's ratio	Density (kg/m^3)
Structural steel	2E+5	1.67E+5	0.77E+5	0.30	7,850
Polyethylene	1,100	2,291	387	0.42	950

3.2 Conceptual models

Conceptual models mean to prepare alternative models for a structure. In this part, designers develop various models such as simple and complex shapes. This step is the most interactive section for the design and main aim of developing conceptual models is to consider all possible options. Developed conceptual models depend totally on the imagination, skills and experience of the designers.

In this study, five different conceptual models were developed and it was considered to cover the equal area for all of them. Although there is infinite number of other potential models and some of them surely fit the purpose even better, the fact about optimization approaches is that it is never possible to achieve the global optimum, but just the local optimum result. Since main goal of this study is to investigate the success of finite element method while considering specified structural criteria, it is possible to apply the current design approach on every sort of different models. Moreover, several systems, which are the most popular styles of the carport structures, were used in this study. For model-1 and model-2, a sloping flat roof type was used. On the other hand, a concave roof type was preferred for model-3, model-4 and model-5. These types of roofs were designed in order to provide maximum vehicle coverage and aesthetic. Developed conceptual models in this study are shown in Fig. 4.

4. Numerical models

Numerical models are mathematical expression of a structural member or system and they are used to determine the structural behaviour that might be subjected to multiple load cases. Therefore, numerical modelling is a beneficiary method in terms of the mathematical modelling of the structures. Numerical modelling of structures gets easier owing to the improvements in computer technologies day by day. In the scope of this study, conceptual models were numerically modelled using ANSYS Workbench [20] software. Finite element model was constituted with SOLID186 elements, which have quadratic 20-noded hexahedrons/10-noded tetrahedrons, and three degrees of freedom per node. Meshing was generated according to the complexity of the designs and adequate refinement was applied on some of the regions, which were determined subsequent to the pre- and post-analysis checking. This is why the number of nodes and elements for some of the designs vary. Fig. 5 shows the numerical model properties of the carport structures with the illustration of the meshed designs.

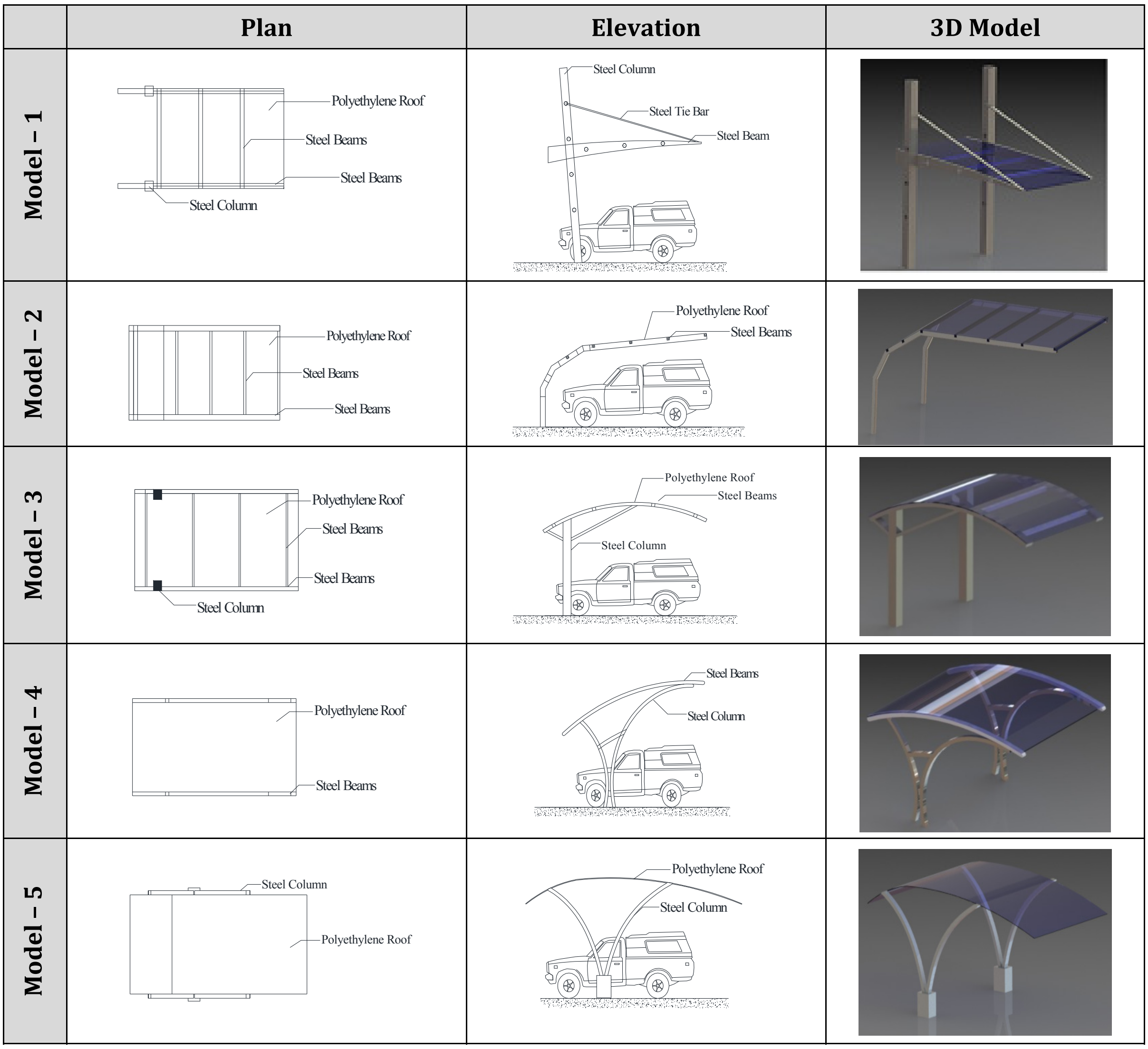


Fig. 4 Conceptual carport models

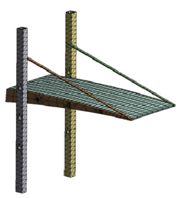
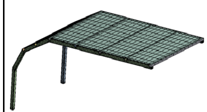
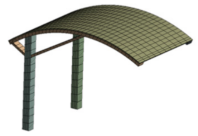
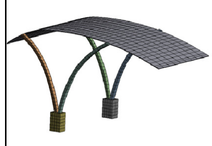
	Model - 1	Model - 2	Model - 3	Model - 4	Model - 5
Elements	20016	21584	3724	7286	1684
Nodes	110963	58192	26332	21765	12943
Numerical Model					

Fig. 5 Finite element parameters of the conceptual models

5. Finite element analysis

Material types were assigned to the structural components of the carport structures from the ANSYS material library. These materials are polyethylene and structural steel for the roof and load carrier parts, respectively. Three types of analyses were performed for each of the models. One of them is the modal analysis that examines the structural behaviour for the first mode, while the others are static structural analyses for snow and wind loadings. According to the assumptions based on international building codes, a snow load of 750 Pa was applied vertically on the roof. Wind load was applied only to the roof because lateral loading to the carrier parts could be neglected owing to their inconsiderable surface areas. Additionally, simplification and rounding off but still based on the international codes were preferred for the calculation of wind load distribution in order to generalize the loading effect for all of the structural designs. Therefore, a positive pressure of 400 Pa to the bottom facet and a suction pressure of 200 Pa to the top facet of the roof were applied in the normal direction of surface elements.

With respect to the determination of the optimum design of conceptual carport structures, volumes of the load carrier parts and total displacement values of the whole structure were recorded and used in the performance index formulation. Moreover, it is difficult and complicated to provide analysis results for each node and element. Therefore, contour pictures and scale tables were used to present the results (Figs. 6, 7). In this study, multiple load cases were considered and the FEA results are discussed within the results and discussions section.

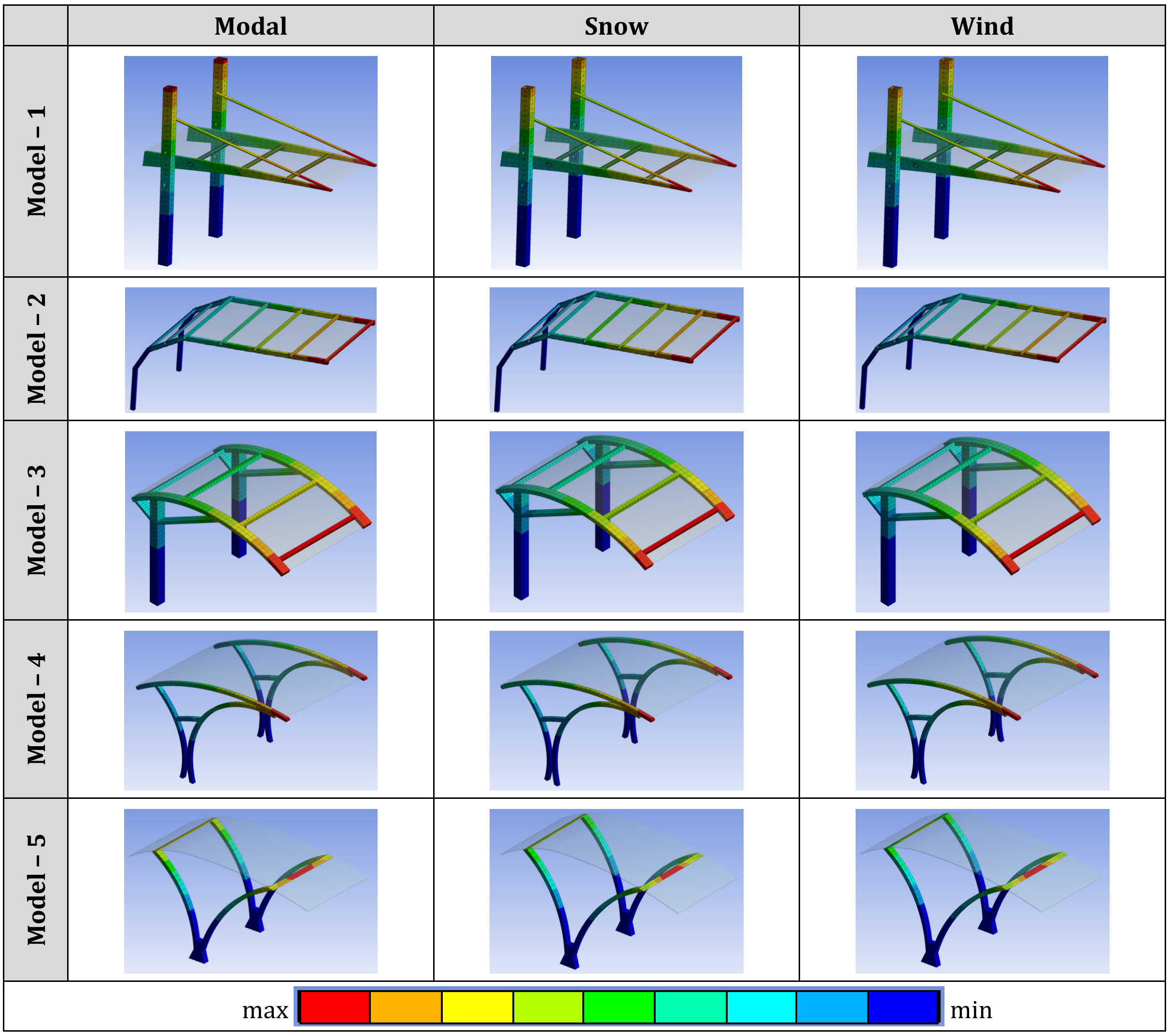


Fig. 6 Total displacement distribution of the steel bearing components

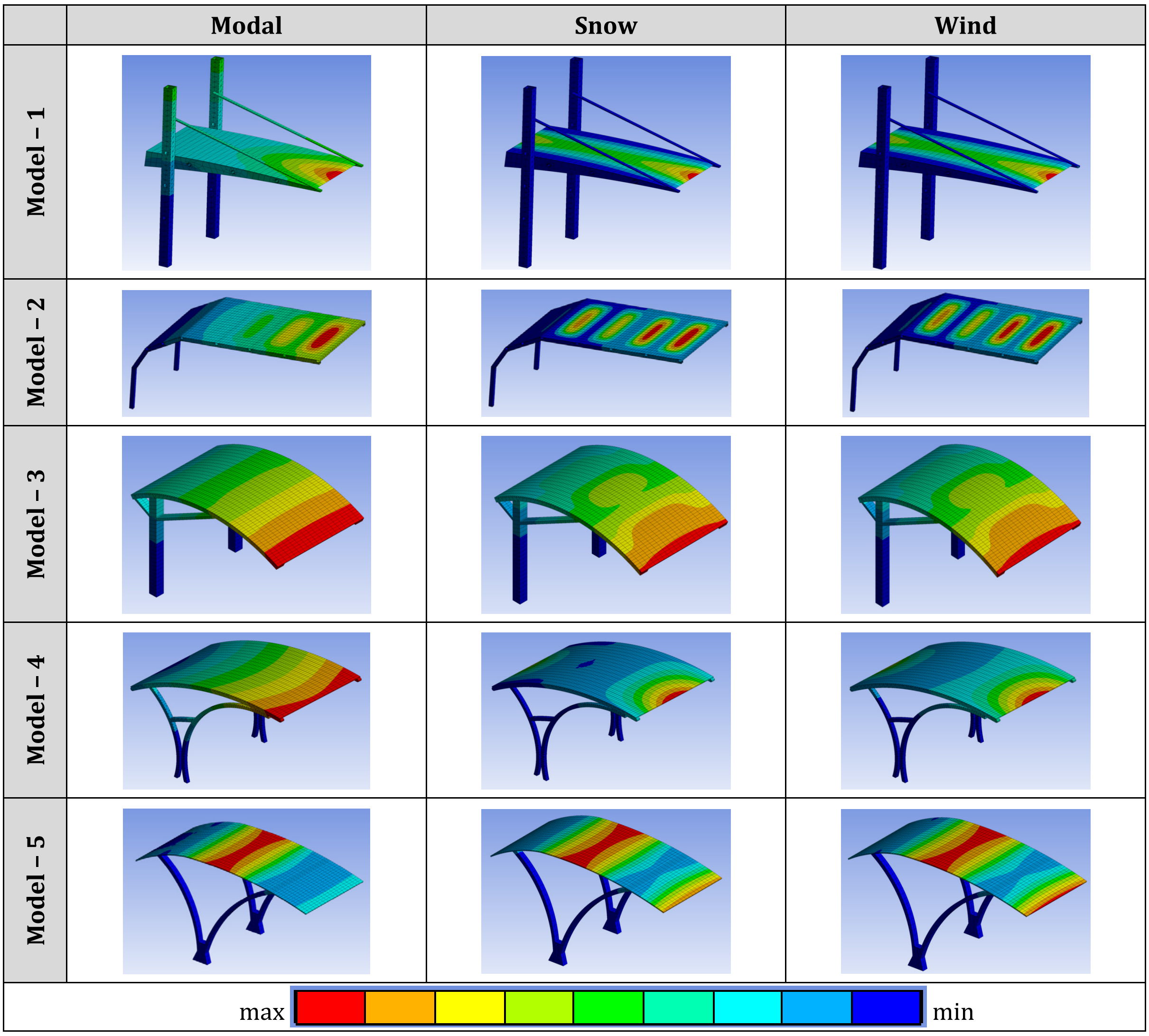


Fig. 7 Total displacement distribution of the all structural components

6. Determination of the optimum design

A structural designer should consider the effective use of materials along with the safety limit and esthetical semblance objectives. Although this point has been investigated in detail by several researchers over the last few decades, manufacturers generally put the semblance forward for the purpose of commercial concerns and push the structural performance of their designs into background.

If a technique is sought in order to answer the question "Which one is the best?", a performance qualification method is needed to be constituted subsequent to the definition of all the design criterions [21]. In this study, five types of popular carport designs covering equal areas were evaluated. Because expected consumer benefit equality is provided for all of the models, there is no need to consider this factor. Furthermore, it should be noted that each product, including carport structures, must be optimized not only based on material concerns or structural behaviour, but also by considering the easy-for-manufacture and easy-for-assembly paradigms. The most suitable design is usually a compromise among the above mentioned requirements. Because current study deals with the rough design at the pre-production stage, it has also been neglected for the aim of obtaining optimum result. For instance, a stability analysis incorporating structural assembly details that was studied by Manifold [22] or a geotechnical investigation that was studied by Hrestak et al. [23] could be integrated as a post-verification stage to the design process in order to make sure every constraint is satisfied before the production.

Design objective for a carport structure could be summarized as satisfying material efficiency objective while maintaining a rigid behaviour against various possible load cases. Although uniform stress levels for the whole structure will assist material efficiency, size and shape dissimilarity of finite elements prevent an accurate calculation. Hence, a new modified performance index formulation, based generally on the nodal displacement levels, should be built according to the following problem definition:

minimize $\quad W = \sum_{e=1}^{t} \rho \, V_e$

subject to $\quad u_{max} \leq u_{max}^{*} \quad \Rightarrow \quad \frac{u_{max}^{*}}{u_{max}} \geq 1$

$\quad u_{avg} \geq u_{avg}^{*} \quad \Rightarrow \quad \frac{u_{avg}}{u_{avg}^{*}} \geq 1$

where W is the weight of the structure, ρ is the material density, V_e is the volume of the eth element, t is the total number of elements, u_{max} is the absolute value of the maximum nodal displacement, u_{avg} is the absolute value of the average nodal displacement value while u_{max}^{*} and u_{avg}^{*} are the upper and lower bound limits of the displacement constraints, respectively.

For the determination of the optimality of carport designs, a performance index, which could be applied in a general scope and considers all the load cases, should be developed step by step. In order to constitute a rigid structure, structural performance level based on the maximum displacement value of the ith model for the jth load case is firstly defined.

$$\chi_i^{I} = \sum_{j=1}^{n} \left(\frac{u_{max}^{*}}{u_{max}^{ij}} \right) \tag{1}$$

Secondly, the average nodal displacement value should be added to the formulation for the purpose of assisting material efficiency qualification.

$$\chi_i^{II} = \sum_{j=1}^{n} \left(\frac{u_{max}^{*}}{u_{max}^{ij}} \frac{u_{avg}^{ij}}{u_{avg}^{*}} \right) \tag{2}$$

The mathematical definition of structural performance level is finalized by implementing the weight value as follows.

$$\chi_i = \frac{1}{W_i} \sum_{j=1}^{n} \left(\frac{u_{max}^{*}}{u_{avg}^{*}} \frac{u_{avg}^{ij}}{u_{max}^{ij}} \right) \tag{3}$$

However, there is a need to define a reference performance level in order to compare the designs with each other. Considering a certain number of models are evaluated in this study, this reference level could be formulated as the mean performance level of all models.

$$\chi_{ref} = \frac{1}{m} \sum_{i=1}^{m} \left[\frac{1}{W_i} \sum_{j=1}^{n} \left(\frac{u_{max}^{*}}{u_{avg}^{*}} \frac{u_{avg}^{ij}}{u_{max}^{ij}} \right) \right] \tag{4}$$

Finally, a performance index formulation is generated by the proportion of the ith model's and reference performance level values. It is named as PI_{rd} because of the aim to attain a rigid design while minimizing the material weight of the structure; in other words, while maximizing the material efficiency.

$$PI_{rd} = \frac{\chi_i}{\chi_{ref}} = \frac{\frac{1}{W_i} \sum_{j=1}^{n} \left(\frac{u_{avg}^{ij}}{u_{max}^{ij}} \right)}{\frac{1}{m} \sum_{i=1}^{m} \left[\frac{1}{W_i} \sum_{j=1}^{n} \left(\frac{u_{avg}^{ij}}{u_{max}^{ij}} \right) \right]} \tag{5}$$

This performance index is suitable to be used for any type of design optimization or comparison problem in order to determine the optimum structure that achieves a rigid structural behaviour with the efficient material use under multiple load cases. Optimum design selection could be practiced simply by choosing the model that has the greatest performance index.

7. Results and discussions

Five conceptual models of carport structures were analysed and investigated in this study. Expected consumer benefit equality is provided for all of the models because they have equal cover area. Modal analysis and static analyses of snow and wind loadings have been performed for each of the models. Weights of the models were calculated according to the solid volume of geometrical designs and material density of the structural parts. Subsequent to the analyses, maximum displacement and average displacement values of the structural nodes were recorded for the calculation of performance index (PI_{rd}). However, an important decision is needed to be made for the calculation of PI_{rd}. Because carport structures consist of a roof and load bearing parts, which are made of different kinds of material, it would not be completely appropriate to calculate PI_{rd} for the whole model. It should be noted that the maximum displacement was confirmed to occur on the roof part for all of the models and analyses. It is possible to decrease the displacement value of roof parts with the aid of little design modifications that would not substantially affect the structural performance in either a positive nor negative way. Since the structural behaviour of load bearing parts is more important in order to design a rigid model; PI_{rd}, which is calculated just for the load bearing parts, should be considered for the optimum design selection. Performance index values of the whole structure for all of the models are also given in this study for the purpose of providing insight into the performance decision concept. Geometrical properties (volume and weight) of the models, average-maximum displacement values for the multiple load cases (modal, snow and wind loadings) and performance index values are presented in Table 2.

Table 2 Structural analysis results of the conceptual models

	Structural parts	Volume (m^3)	Weight (kg)	Modal		Snow		Wind		PI_{rd}
				u_{avg} (mm)	u_{max} (mm)	u_{avg} (mm)	u_{max} (mm)	u_{avg} (mm)	u_{max} (mm)	
Model - 1	Bearing	0.550	4,318	15.09	26.99	1.56	3.03	1.29	2.50	0.31
	Total	0.909	4,659	15.28	49.97	1.86	27.77	1.53	22.13	0.18
Model - 2	Bearing	0.037	291	41.20	103.27	28.96	69.97	24.90	58.93	3.55
	Total	0.075	326	44.56	160.13	40.54	358.99	34.27	290.77	2.94
Model - 3	Bearing	0.516	4,053	9.84	28.76	1.56	5.13	1.28	4.18	0.20
	Total	1.000	4,512	12.43	29.30	2.05	5.64	1.69	4.59	0.48
Model - 4	Bearing	0.179	1,408	14.13	45.77	3.51	11.78	5.01	15.19	0.56
	Total	0.611	1,818	17.62	45.84	6.89	47.26	8.34	42.63	0.75
Model - 5	Bearing	0.312	2,445	6.28	15.09	6.32	17.35	4.80	13.70	0.39
	Total	0.801	2,910	27.75	92.90	29.36	82.93	22.57	63.07	0.65

According to the performance index values of their load bearing parts, the best carport structure throughout the five conceptual models is model-2. It is seen in Table 2 that PI_{rd} value of model-2 is the highest one by a wide margin in comparison to the other models'. Its PI_{rd} value is 3.55 while the second best model's is 0.56 and the last model's is 0.20. Even though the maximum displacement of the respective model is much higher as well, the closeness of the average displacement values to the maximum and particularly the lowest material weight, suggests that this model to have the best structural performance.

When the differences of PI_{rd} values, which were calculated for the whole of any structural models, are investigated, structural performances of the roof parts should be evaluated carefully. PI_{rd} values for the whole structure of models -1 and -2 are lower than the PI_{rd} values for the bearing parts, while this relation is inverse for the other models. Because the material amount is equal for all the models, one can assume that maximum displacement values of the roof parts of these two models are excessively higher than the values at bearing parts. It is true that maximum displacement values are higher but the reason why PI_{rd} value is higher for models -3, -4 and -5 is that average displacement value increased, as did the maximum displacement value. Therefore, when the structural behaviour of these five carport structures are evaluated by the performance index concept, this method indicates that model-2 has the best structural performance, regardless of having higher displacement values. However, this model can be improved in order to decrease the maximum displacement value by little modifications at lower levels. Magnification of cross-sections or supplementation of new bearing members especially at the most stressed regions will verify this objective without increasing the material weight too much. These modelling modifications should depend on designer's choice or consumer's necessity, also any appropriate geometrical optimization method could be employed as an alternative way.

8. Conclusion

A structural design problem prior to the production stage comes with many questions. These are revision of previous similar solutions, selection of the materials to be used, geometrical modelling method to be performed and determination of the best design throughout the possible designs, respectively. In case there is a need to consider multiple load cases, the complexity of the problem gets bigger. This study seeks the answer to the last question and evaluates five conceptual carport structures depending on a structural performance qualification approach. The main contribution of this research is to develop a performance index formulation in order to determine the best design before the production stage. The study intended to investigate effects of material efficiency and structural rigidity on the design of carport structures by using finite element analysis. For this aim, a performance index formulation was developed to assist the decision of material efficiency as well as structural rigidity, that is called as PI_{rd}. Formulation steps consider the influence of the geometrical properties and finite element analysis results that exhibit the structural behaviour collectively.

Subsequent to the finite element analyses of the conceptual models, which are subjected to multiple load cases, their PI_{rd} values have been calculated and commented with respect to the analysis results. Actually, the best model could have been evaluated as inadequate without any qualification method but the performance index concept leads the way by numerical results and facilitates one of the most important steps of a structural design problem.

Additionally, the production process of any type of structure involves not only materials from which the product is made of, but also the manufacturing processes, machine tools, tools, fixtures, assembly process, environment requirements etc. Integrating also esthetical semblance will make the optimum design problem more complex, however, conducting a questionnaire throughout the sectoral experts to attain a sensitivity degree is possible. In order to overcome manufacturing related concerns, modification of performance index formulation using that sensitivity degree or consulting some other optimization methods such as fuzzy logic could be considered in future studies.

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