Effects of Material Changes on the Performance of Industrial Trusses: A Simulation Approach

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Abstract: ***For many years, trusses have served as one of the excellent load carrying members for domestic and industrial buildings, and are becoming more-and-more useful day-by-day. Considering these facts Present research work is devoted to the investigations on the performance evaluation of trusses under different materials. For this purpose, three industrial trusses, namely, Howe truss, Pratt truss and Warren truss are designed, and performance parameters, maximum compressive force, maximum tensile force, maximum, shear, maximum bending moment under compression and node displacement for each alternative under two different materials, hot rolled steel and cold forged steel, are investigated. In next step, in order to get common ranking, a well known statistical technique, coefficient of variance is used. Results of the research work show the suitability of cold forged steel for truss making applications. Results also show that cold forged Warren truss shows the best performance out of the available alternatives.***

Keywords: Trusses, hot rolled steel, cold forged steel, Howe truss, Pratt truss, Warren truss

1. Introduction

A truss is a structure where each element, typically a bar, only supports tension or compression forces because it is connected to other bars through what are assumed to be multiple spherical joints, although in some cases the joints may be separated in the actual construction. Truss structures and space frames have long been preferred solutions to the problem of maximizing structural efficiency, as they allow for very large increases in the flexural rigidity and load carrying capacity achievable from a given amount of material. The primary advantage of a truss over a monolithic or tubular structure is that grouping the material available into discrete local beam members allows for the overall size of a structure built from a given amount of material to be increased to take advantage of the highly non-linear scaling laws governing bending stiffness and strength (as determined by equivalent flexural rigidity) without being overly restricted by the strength limitations inherent in trying to make large, thin walled tubular structures. Another key advantage of truss structures is that they divide the large structure into a number of local members which due to their slenderness, straightness, and attachment methods are able to act in a manner which approaches an ideal two-force member. A two force member, unlike a beam, experiences only tensile and compressive forces. Structures are considerably stiffer and stronger under axial loading then they are under bending loading, and so the use of trusses allows the material to experience lower stress levels and to be used more efficiently. In present research work, investigations on the effect of material changes on industrial trusses are made. In the research work, three types of trusses, Pratt, Warren and Howe, are considered and their performance under two materials, hot rolled steel and cold formed steel, is evaluated. For the purpose of evaluation well known structural analysis software STADD.Pro V8i SS6 is used.

1.1 Objectives of the Research Work

Following are the objectives of research work;
1) Analyze the effects of material changes on the performance of different industrial trusses; and
2) Ranking of different combinations of materials and trusses.

2. Literature Review

Present section tells about the academic aspects of the research carried out in the field of trusses, and presents a summary of research contributions in the field of trusses, the details of which are presented in upcoming sections.

2.1 Research contributions in the field of Trusses

Table 2.1 shows the summary of research contributions made by different researchers in the field of trusses.

Table 2.1: Research Contributions in the Field of Trusses

S. No	Researcher (Year)	Contribution
1	Chen *et al.* (2018)	Composite box girders with corrugated steel webs and trusses are a new type of advanced bridge structure proposed recently. This kind of structure consists of a top concrete slab, corrugated steel webs and two bottom concrete-filled steel tubes connected by trusses. The resistance to torsion and overturning of this kind of structure is larger than that of composite bridges with a single concrete-filled steel tube. This kind of structure is able to satisfy the requirement of rapid construction, environment protection and cost effectiveness. Two composite box girder bridges with corrugated steel webs and trusses have been or are being constructed in China. This paper presents the design of these two bridges in detail, which will provide valuable engineering experience for the further promotion of this kind of new bridge structure. Experimental research has been carried out to study the flexural behavior and the flexural capacity of this kind of new bridge structure. The test results show that when the test beam is at the elastic stage, the cross-section can be viewed as a plane section if only the strains of the concrete top slab and the bottom steel tubes are considered. The test beam shows good ductility throughout the whole loading process.
2	Huang *et al.* (2018)	This paper investigates the behavior of Warren-vertical CFT truss girders by conducting both experimental tests and finite element analyses. Experimental tests on three CFT truss girders are first conducted. The test parameter is the compressive strength of the concrete infill. Finite element models, which were developed and benchmarked previously by the authors, are then used to further investigate the behavior of CFT truss girders and the influence of parameters such as the brace-to-chord strength ratio, shear span-to-depth ratio, and concrete compressive strength. Results from the parametric studies indicate that CFT truss girders are flexure dominated if (i) the brace-to-chord strength ratio ≥0.8 and (ii) the shear span-to-depth ratio ≥4.8. Both the experimental tests and FEM analyses indicate that the concrete compressive strength has negligible effects on the failure mode of CFT truss girders. Based on results from the experimental tests and FEM analyses, design equations are also proposed for estimating the flexural strength of Warren-vertical CFT truss girders.
3	Hou *et al.* (2017)	Concrete filled steel tubular truss (CFST truss for short) structures composed of CFST members as chords and steel tube members as braces are having expanded utilization in large-scale infrastructure constructions. In bridge structures, a concrete slab is usually provided on top of the CFST truss to form a hybrid CFST truss. Besides previous research work on the experimental performance of CFST and hybrid CFST trusses reported in the companion paper (Han et al., 2015), detailed analytical behavior of such composite truss systems is needed. This paper thus presents a finite element analysis (FEA) modeling on CFST truss without concrete slab as well as hybrid CFST truss with concrete slab subjected to flexural loading, which is validated through reported test data. The FEA modeling is then used to perform analysis on typical failure modes, moment-deflection relations, stress developments, material interactions and the load transferring paths of the composite truss systems. Influences of important parameters on the flexural performance of the composite truss are also investigated, including chord types, existence of reinforced concrete (RC) slab, strength ratio between chords, cross-section profiles, etc. Finally, simplified methods for calculating the flexural strength of CFST and hybrid CFST trusses are recommended and validated.
4	Porta and Thomas (2017)	Variable geometry trusses are composed, in general, of unit cells which can be modeled as bars connected by spherical joints. Under mild conditions, it has been shown that the only feasible cells are topologically equivalent to bi pyramids. Unfortunately, using standard formulations, the closed-form position analysis of bi pyramids is not a trivial task. Actually, it has only been achieved for bi pyramids with up to 7 vertices, whose closure polynomial has been shown to be of order 24. In this paper, using a distance-based formulation and a kinematic inversion for fans of tetrahedra, the problem is solved for bi pyramids with up to 11 vertices, whose closure polynomial is of degree 896. No other position analysis problem leading to such a high-order closure polynomial has been previously solved.
5	Zeynalian *et al.* (2016)	This paper presents an experimental study on the behavior of cold formed steel truss connections. Eighteen full scale cold-formed steel truss connections were tested. Of particular interests are the specimens maximum load capacity and the load-deformation behavior. The study also looks at the failure modes of the connections. The behaviors exhibited by the connections are discussed and the design capacities calculated from the current CFS design standards are compared to the experimental results of the connections. This study investigates the main factors contributing to the ductile response of the CFS truss connections in order to suggest recommendations for connection designs, and improvements so that the connections respond plastically with a significant drift and without any risk of brittle failure. Also, a number of alternative fasteners are chosen and investigated for comparison with those that are currently specified for trusses' connections.
6	Xu *et al.* (2016)	This study presented a new method for forming the graded corrugated truss core sandwich structures based on an auto-cutting and mould-press process. The bending stiffness, strength and failure mechanism were investigated. Analytical models were presented to estimate the performance and failure mode of the sandwich beams. In order to demonstrate sensitivity of geometric parameters on the bending behavior of the truss core sandwich beams, a uniform and two kinds of graded corrugated truss core sandwich panels were fabricated and tested to probe different failure modes. Results showed that the distributions of the truss cores have strong influences on the bending behaviors of the sandwich beams. The predicting results were also compared with the measurements investigated. In general, the measured failure loads showed good agreement with the analytical predictions, except the uniform truss core sandwich beam. The graded corrugated truss core sandwich structures investigated appear to be promising candidates for lightweight systems and multifunctional applications.

2.2 Gaps in the Existing Research

On the basis of survey of above literature, following research gaps are being identified.

1) There is very limited research which compares different industrial trusses; and
2) There is almost none research available which analyses the effects of material changes on the performance of trusses.

3. Solution Methodology

Present chapter tells about the details of parameters investigated and software used for the research work, the details of which are presented in upcoming sections.

3.1 Investigated Parameters in the Research

Following parameters are being investigated in the research work.

1) **Maximum Tensile Force**
It is defined as the maximum value of force due to tension effects in the member or assembly of members of truss;

2) **Maximum Compressive Force**
It is defined as the maximum value of force due to compression effects in the member or assembly of members of truss;

3) **Maximum Shear**
It is defined as the maximum value of force due to shear effects in the member or assembly of members of truss;

4) **Bending Moment in Compression**
It is defined as the summation of all bending moments from one end to the other end, in the beam when compressive load is applied on it; and

5) **Node Displacement**
It represents the maximum displacement of the member from designed location.

3.2 Software used in Research Work

The software used in the research work is STADD.Pro. STAAD or (STADD.Pro) is a structural analysis and design computer program originally developed by Research Engineers International at Yorba Linda, CA in 1997. In late 2005, Research Engineers International was bought by Bentley Systems. An older version called Staad-III for Windows is used by Iowa State University for educational purposes for civil and structural engineers. The commercial version, STADD.Pro, is one of the most widely used structural analysis and design software products worldwide. It supports several steel, concrete and timber design codes.

It can make use of various forms of analysis from the traditional 1st order static analysis, 2nd order p-delta analysis, geometric non-linear analysis, Pushover analysis (Static-Non Linear Analysis) or a buckling analysis. It can also make use of various forms of dynamic analysis from modal extraction to time history and response spectrum analysis.

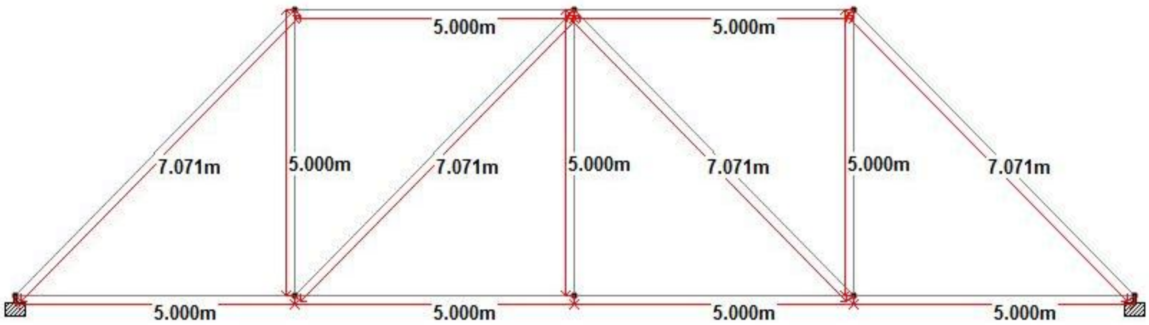
In recent years it has become part of integrated structural analysis and design solutions mainly using an exposed API called OpenSTAAD to access and drive the program using a Visual Basic macro system included in the application or by including Open STAAD functionality in applications that themselves include suitable programmable macro systems. Additionally, STAAD.Pro has added direct links to applications such as RAM Connection and STAAD. Foundation to provide engineers working with those applications which handle design post processing not handled by STAAD.Pro itself. Another form of integration supported by the STAAD.Pro is the analysis schema of the CIMsteel Integration Standard, version 2 commonly known as CIS/2 and used by a number modeling and analysis applications.

4. Problem Formulation and Solution

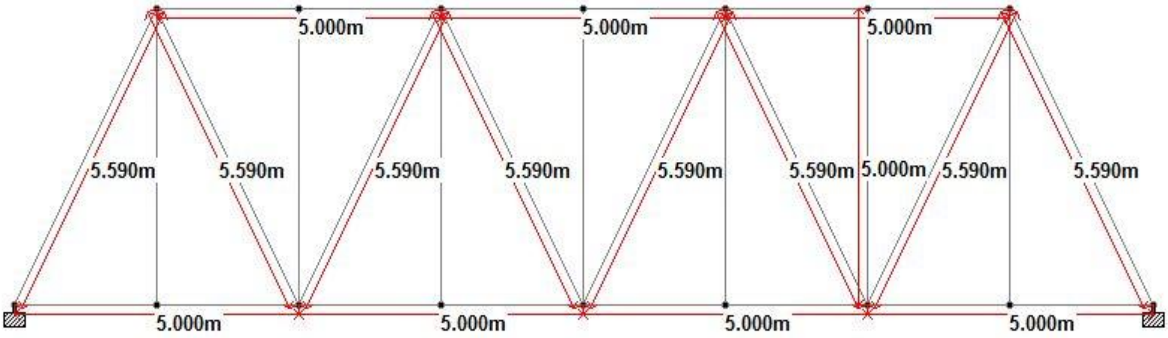
Present section tells about the details of implementation of research tools on the case problem, the details of which are presented in upcoming sections.

4.1 Problem Formulation

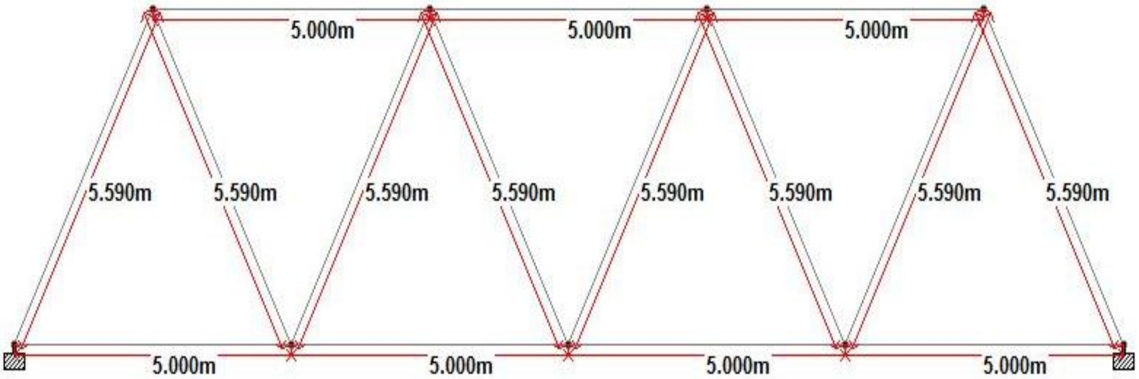
In order to solve any problem, the first step need is a systematically designed problem. Problem formulation is defined as a first step of a solution. The research problem was the comparison of Howe, Pratt and Warren trusses using different materials. For this purpose, first of all models of different trusses were designed in a modeling software, STADD.Pro V8i SS6, the details of which are presented as follows.



(a) Howe Truss



(b) Pratt Truss



(c) Warren Truss

Figure 4.1: Models of different types of Industrial Trusses

Details of properties and reports obtained are presented in Appendix I.

Following are the details of properties of materials used.

Table 4.1: Properties of the materials used(www.makeitfrom.com)

S. No.	Property	Unit	Hot Rolled Steel	Cold Rolled Steel
1	Young's Modulus	GPA	190	190
2	Poisson's Ratio		0.29	0.29
3	Density	gm/cm^3	8	7.8
4	Thermal Coefficient	/^{0}C	1.20E-05	1.20E-05
5	Critical Damping coefficient		0.03	0.03
6	Shear Modulus	GPA	73	73

4.2 Solution of the Problem

In next step, with the help of expert's opinion, different load combinations were applied to the models, the details of which are presented as follows.

Types of loads:

a) Live load
b) Dead Load
c) Wind Load

Load Combinations:

a) 1.5 (DL + LL)
b) 1.2 (DL +LL +WL)
c) 1.2 DL + 1.2 LL + (-1.2 WL)
d) 1.2 (DL + LL)
e) 1.5 (DL + WL)
f) 1.5 DL + (-1.5 WL)
g) 1.5 DL
h) 0.9 DL

In next step, loads applied to all different models, the details of which are presented as follows.

Table 4.2: Details of Loads

S. No	Type of Load	Factor	Magnitude	Position
1	Self-weight	1.5		Member load
2	UDL		1 kN/m	Member load
3	Live load		10 kN/m	Load on bottom chord

After application of loads, results were analyzed.

5. Results and Discussion

The section tells about the results yielded out of the analysis as well as discussion, the details of which are presented in upcoming sections.

5.1 Results

Table 5.1 tells about the summary of results obtained.

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Table 5.1: Summary of Results

S. No	Type of Truss	Forces		Maximum Bending Moment in compression	Maximum Torsion	Node Displacement
		Maximum Axial Force	Maximum Shear			
1.	CFS-Howe	143.092	39.004	83.428	0.286	18.305
2.	CFS-Pratt	183.589	25.578	114.449	0.596	18.703
3.	CFS-Warren	143.902	39.004	83.428	0.286	15.455
4.	HRS-Howe	144.015	39.319	82.800	0.690	3.418
5.	HRS-Pratt	185.503	25.833	113.196	1.908	15.781
6.	HRS-Warren	169.632	40.037	77.835	0.566	13.406

Graphical representation above results is presented as follows.

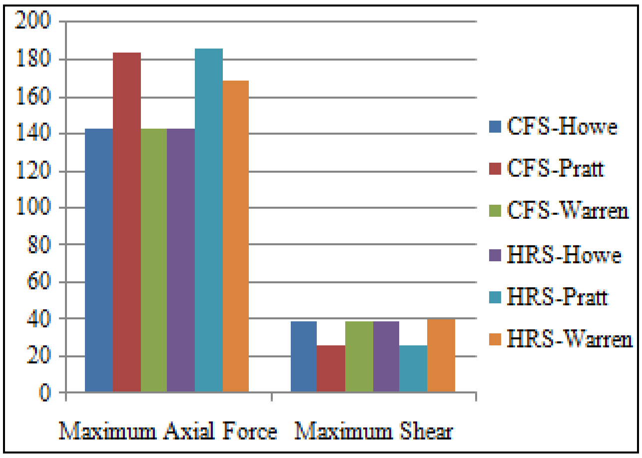

Figure 5.1: Graphical Representation of Results for Different Forces

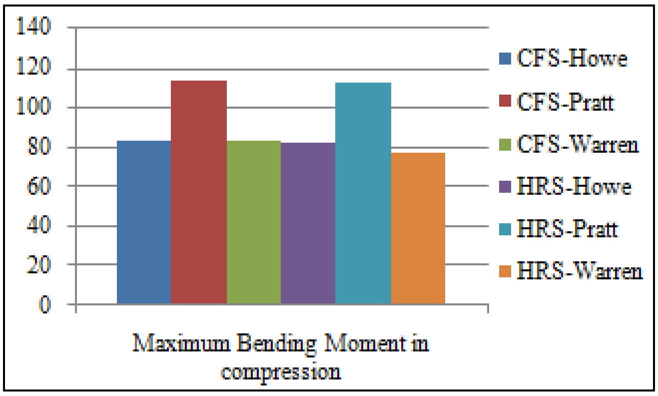

Figure 5.2: Graphical Representation of Results for Maximum Bending Moments in Compression

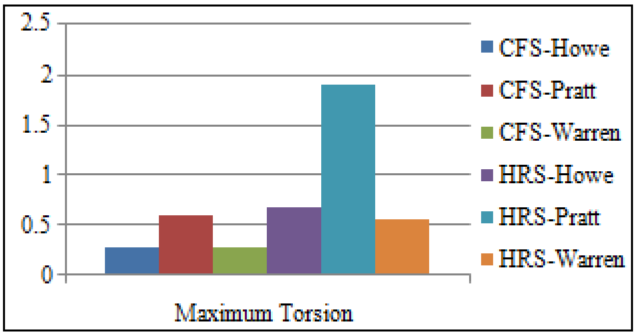

Figure 5.2: Graphical Representation of Results for Maximum Torsion in Compression

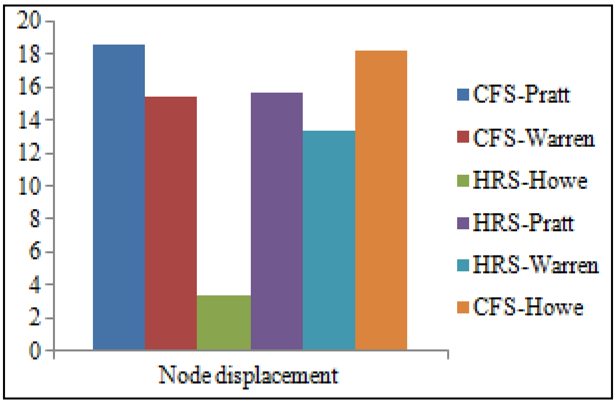

Figure 5.3: Graphical Representation of Results for Maximum Node Displacement

5.2 Discussion

From results obtained from Table 5.1 and Table 5.1, rankings to the trusses made of two materials can be assigned, as follows.

Table 5.2: Ranking of Materials

S. No	Type of Truss	Maximum Axial Force	Rank	Maximum Shear	Rank	Maximum Bending Moment in compression	Rank	Maximum Torsion	Rank	Node Displacement	Rank
1	CFS-Howe	143.902	1	39.004	3	83.428	3	0.286	1	18.305	5
2	CFS-Pratt	183.589	4	25.578	1	114.449	5	0.596	3	18.703	6
3	CFS-Warren	143.902	1	39.004	3	83.428	3	0.286	1	15.455	3
4	HRS-Howe	144.015	2	39.319	4	82.800	2	0.690	4	3.418	1
5	HRS-Pratt	185.503	5	25.833	2	113.196	4	1.908	5	15.781	4
6	HRS-Warren	169.632	3	40.037	5	77.835	1	0.566	2	13.406	2

Table 5.2 shows the absence of common ranking scored by different trusses. For rank 1 CFS-Howe and CFS-Warren truss show their suitability for criteria maximum axial force and maximum torsion. For the same ranking CFS Pratt truss shows its suitability for the criteria maximum shear. In the similar manner HRS-Howe truss earns the same rank for criteria node displacement, and HRS-Warren gets the rank for criteria maximum bending moment.

For rank 2, HRS-Howe truss acquires the rank for criteria maximum axial force and maximum bending moment, HRS-Pratt truss gets the rank for criteria maximum shear force, whereas HRS-Warren truss earns the rank for criteria maximum torsion and node displacement.

For rank 3 CFS-Howe truss and CFS-Warren truss show their suitability for criteria maximum shear force and maximum bending moment, while CFS-Pratt truss scores for this rank on maximum torsion. Similarly, HRS-Warren earns the rank for criteria maximum axial force. CFS-Warren truss also shows its suitability for the same rank on criteria node displacement.

For rank 4, HRS-Howe truss shows its suitability on maximum shear and maximum torsion. Similarly, CFS-Pratt truss earns the rank for maximum axial force, and HRS-Pratt truss for maximum bending moment and node displacement.

For rank 5, CFS-Pratt scores for the criteria maximum bending moment, whereas for criteria maximum torsion and axial force, HRS-Pratt truss seems to be appropriate. On criteria Maximum shear, HRS-Warren truss also appears for rank 5, whereas for criteria node displacement CFS-Howe truss is appropriate. On criteria node displacement CFS-Pratt truss appears for rank 6.

From Table 5.2, following points can be noted.
- There is the absence of common ranking of different trusses on different criteria; and
- There is absence in common rankings based on truss materials.

Therefore, in order to get a common ranking, a statistical tool, coefficient of variance was calculated for different criteria were calculated. Coefficient of variance is defined as the ratio of standard deviation to the average for scores in percentage. While dealing with parameter, the ranking procedure for the criteria is selected for which value of coefficient of variance is minimum. Table 5.3 shows the details of coefficient of variance for different criteria.

Table 5.3: Details of Coefficient of Variance for different Criteria

S.No	Parameter	Maximum Axial Force	Maximum Shear	Maximum Bending Moment in compression	Maximum Torsion	Node Displacement
1	Standard Deviation	20.27267	7.051908	16.63631	0.604653	5.62284
2	Average	161.7572	34.79583	92.52267	0.722	14.178
3	Coefficient of Variance	0.125328	0.202665	0.179808	0.837469	0.7028
4	%Coefficient of Variance	12.53278	20.26653	17.9808	83.7469	70.28
5		**Preferred Ranking**				

According to Table 5.3 ranking of trusses should be done on the basis of maximum compressive force, based on which overall rankings are presented as follows.

Table 5.4: Overall Rankings of Trusses

S. No	Truss	Rank
1.	CFS-Howe	1
2.	CFS-Pratt	4
3.	CFS-Warren	1
4.	HRS-Howe	2
5.	HRS-Pratt	5
6.	HRS-Warren	3

6. Conclusion, Limitations and Future Scope of the Research

Present section tells about the conclusion, limitations and future scope of the research, the details of which are presented in upcoming sections.

6.1 Conclusion

In present research work, comparison of two well known truss building materials, hot rolled steel and cold forged steel is made for industrial truss applications. For this purpose, three types, namely, Howe truss, Pratt truss, and Warren truss, were designed in STADD.Pro software and *five* parameters, maximum axial force, maximum shear, maximum bending moment and maximum node displacement were investigated for all the alternatives made up of hot rolled steel and cold forged steel. Due to unavailability of common rankings, coefficients of variance of alternatives were calculated, which give the rankings of trusses as well as suitability of materials. Following points represent the conclusion drawn from the research work.
1) Out of the available options, best material for industrial truss application is cold forged steel;
2) Out the three alternatives, best truss designs are Howe and Warran trusses; and
3) Second best truss design is HRS-Howe truss.

6.2 Limitations and Future Scope of the Research

Following points represent the limitations of present research work.
1) The research work is limited to a particular set of truss materials;
2) The research is also limited to limited designs of trusses; and
3) The research is also limited to the investigations of limited properties of trusses.

Based on above limitations, following points indicate the future scope of the research work.
1) A detailed research work, including a broader set of truss materials can be initialized;
2) An extensive research work consisting of a detailed set of truss designs can is still awaited; and
3) A detailed research work considering investigations on a broader set of truss properties is can be initiated.

References

[1] Hou, C., Han, L. H., Mu, T. M., & He, S. H. (2017). Analytical behavior of CFST chord to CHS brace truss

under flexural loading. *Journal of Constructional Steel Research*, 134, 66-79.

[2] Zeynalian, M., Shelley, A., & Ronagh, H. R. (2016). An experimental study into the capacity of cold-formed steel truss connections. *Journal of Constructional Steel Research*, 127, 176-186.

[3] Xu, G. D., Yang, F., Zeng, T., Cheng, S., & Wang, Z. H. (2016). Bending behavior of graded corrugated truss core composite sandwich beams. *Composite Structures*, 138, 342-351.

[4] Porta, J. M., & Thomas, F. (2017). Closed-form position analysis of variable geometry trusses. *Mechanism and Machine Theory*, 109, 14-21.

[5] Chen, Y., Dong, J., & Xu, T. (2018). Composite box girder with corrugated steel webs and trusses–A new type of bridge structure. *Engineering Structures*, 166, 354-362.

[6] Huang, W., Lai, Z., Chen, B., Xie, Z., & Varma, A. H. (2018). Concrete-filled steel tube (CFT) truss girders: Experimental tests, analysis, and design. *Engineering Structures*, 156, 118-129.