STUDY ON CONCRETE INFILLED TUBES AS COMPRESSION MEMBERS IN TRUSS TYPE LIGHT VEHICULAR BRIDGES

P. B. M. R. Bogahawaththa

198023U

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

Sri Lanka

April 2021

STUDY ON CONCRETE INFILLED TUBES AS COMPRESSION MEMBERS IN TRUSS TYPE LIGHT VEHICULAR BRIDGES

P. B. M. R. Bogahawaththa

198023U

Thesis submitted in partial fulfilment of the requirements for the degree Master of Science in Civil Engineering

Department of Civil Engineering

University of Moratuwa

Sri Lanka

April 2021

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)

…… Date:

P. B. M. R. Bogahawaththa

The above candidate has carried out research for the Masters under my supervision.

…… Date:

Dr. H. D. Hidallana-Gamage

…… Date:

Dr. K. Baskaran

ABSTRACT

Applicability of concrete filled steel tubes (CFST) for compression members in truss type steel light vehicular bridges is studied in this research as an economical solution for the lack of light vehicular bridges in Sri Lanka. There are many places in Sri Lanka where people have to travel long distance to cross rivers or access the nearby city for their day to day needs. CFST is a composite material which is getting more popular in the civil engineering industry. So, it is important to examine the properties of CFST as a composite material. The use of CFST in truss bridges has several advantages such as deflection reduction of the bridge, improved seismic performance, improved load carrying capacity, dynamic performance, and cost reduction. To achieve an economical structural performance, CFST section has to be designed properly. Optimum positions to use CFST have to be identified depending on the truss type. Replacing larger steel I sections with CFST will reduce the cost since the same amount of force can be carried out with less steel amount in CFST. Also, the tendency to local buckling is reduced when thinner sections are filled with concrete. Therefore, to achieve a higher span with a lesser cost (steel tonnage), usage of CFST sections for compression members have been accessed in this study. Also, the tendency to local buckling was examined with experimental and numerical simulations. Hence first, a desk study was carried out focusing Gin Ganga area to identify the problems in the area due to lack of bridges. Two experimental model bridges were tested in this study as one with only hollow aluminium tubes and other with cement grout filled in selected top chord members. Using a real scale numerical simulation of a CFST bridge model, practical applicability and cost figures were compared with a conventional steel truss bridge.

Keywords: truss type steel light vehicular bridges, concrete filled steel tubes, composite material, axial compression, finite element modelling

DEDICATION

To my loving parents, brothers and sisters for encouraging me throughout the milestones of my life and my supervisor, Dr. Hidallana-Gamage H. D. and co-supervisor Dr. Baskaran K. for the unwavering motivation and mentorship they provided.

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude towards my supervisor, Dr. Hidallana-Gamage H. D. for motivating me to explore the bridge engineering arena and supporting me to build up my research. His invaluable guidance to help me keep up with the timeline and produce results, while overcoming the hurdles is greatly acknowledged. I would also like to express my thanks to my co-supervisor, Dr. Baskaran K., for the enthusiasm and motivation he planted in me to pursue my research.

Next, I extend my sincere gratitude to Prof. M. T. R. Jayasinghe and Dr. (Mrs.) J. C. P. H. Gamage for their valuable comments, recommendations and suggestions given during the progress reviews which helped me to further improve my work. Then I would like to thank Dr. (Mrs.) M. T. P. Hettiarachchi and Dr. G. Tharmarajah for their valuable comments and recommendations given as members of the examination panel. I would also like to take this opportunity to express my sincere gratitude to all the academic staff of the Department of Civil Engineering, University of Moratuwa, for laying a strong technical foundation in my undergraduate studies.

I thank my fellow research assistants for the constructive discussions we had that supported me in using numerous approaches to overcome research questions, and I appreciate the support they have given for conducting the laboratory experiments. I would also like to thank the technical staff members in the Department of Civil Engineering, who supported me in building the experimental models. I am also grateful to all other academic and non-academic staff of the Department of Civil Engineering and my colleagues for their support during the research.

Finally, I would like to thank the Senate Research Grants Committee (SRC) for the financial assistance provided throughout this project.

CONTENTS

Declaration i

Abstract ii

Dedication iii

Acknowledgement iv

List of Figures x

List of Tables xiv

1. Background 1

1.1. Introduction 1

1.2. Importance and Identification of Knowledge Gap 3

1.3. Aim and Objectives of the Research 4

1.4. Methodology 4

1.5. Significance of the research 5

1.6. Outline of the Thesis 6

2. Review of previous literature 7

2.1. Background 7

2.2. Concrete filled steel tubes 8

2.2.1. Behaviour of CFST under different stress conditions 9

2.2.2. Effect of corrosion on CFST 13

2.2.3. Constructability 15

2.3. Truss Bridges 16

2.3.1. Introduction 16

2.3.2. Truss bridges in Sri Lanka 18

2.3.3. Force distribution in truss bridges 19

2.4. CFST in truss bridges 19

2.4.1. World practice 21

2.4.2. Sri Lankan practice 22
2.5. Theoretical analysis of steel tubes for compression 22
2.5.1. Hollow steel tubes 22
2.5.2. CFST sections 23
2.6. Finite element modelling 24
2.6.1. Introduction 24
2.6.2. Mander, Priesley and Park (1988) 25
2.6.3. Hu at el. (2007). 26
2.6.4. Moon et al. (2012) 31
2.7. Cost benefit analysis 33
2.8. Chapter Summary 35
3. Desk Study 37
3.1. Existing Pedestrian bridge types and condition in Sri Lanka 37
3.2. Reasons for the scarcity of pedestrian bridges in necessary areas 40
3.3. Preliminary truss analysis using numerical software 41
3.3.1. Finite element (FE) modelling 47
3.3.2. Span Vs. Tonnage graphs 47
3.3.3. Loads on bridges 48
3.3.4. Discussion of results 52
3.4. Identification of the problems in the existing pedestrian bridges and propose strengthening measures 53
3.5. Chapter Summary 55
4. EXPERIMENTAL PROGRAM PHASE 1 - Compression testing of square hollow GI sections and CFST 57
4.1. Introduction 57
4.2. Theoretical prediction of the failure loads and modes 59

4.3. Failure loads and modes obtained from the experiment 62

4.4. Comparison of the experimental results with the theoretical predictions ……..67

4.5. Strength enhancement of CFST compared to hollow GI tubes 69

4.6. Chapter Summary 72

5. Experimental Program Phase 2 – Testing model bridges 74

5.1. Introduction 74

5.2. Details of the model bridges 74

5.3. Tensile test on Aluminium sections 76

5.4. Compression testing of Aluminium hollow and Aluminium grout filled tubes (GFAT) 77

5.4.1. Theoretical prediction of the failure loads and modes 77

5.4.2. Experimental failure loads and modes 78

5.4.3. Comparison of the experimental failure loads and modes with theoretical predictions 80

5.4.4. Strength enhancement of GFAT compared to hollow Aluminium tubes ……..81

5.5. Laboratory testing of model bridges 82

5.5.1. Predicting the theoretical failure loads of the bridge models ……..84

5.5.2. Experimental model loading 85

5.5.3. Experimental test results 87

5.5.4. Comparison of the experimental results with the theoretical predictions ……..93

5.5.5. Strength enhancement in the truss with GFAT (Truss B) compared to that with Aluminium hollow sections (Truss A) 95

5.6. Chapter Summary 96

6. Numerical analysis 98
6.1. Introduction 98
6.2. FEM Software 98
6.3. FEM Details 98
6.3.1. Concrete 98
6.3.2. Steel 103
6.3.3. Parts 103
6.3.4. Interaction 104
6.3.5. Loading and Boundary Conditions 104
6.4. Results of FEM 104
6.5. Chapter Summary 110
7. Application of cfst in truss type light vehicular bridges 111
7.1. Introduction 111
7.2. Methodology 111
7.3. FE Analysis of the selected bridge types 112
7.3.1. Bridge loading 112
7.3.2. Material properties 113
7.4. Design of CFST truss bridge 113
7.5. Results and comparison 116
7.6. Feasibility study 117
7.6.1. Economic feasibility 117
7.7. Constructability 120
7.8. Chapter summary 120
8. Conclusion 122
Recommendation for future work 126
REFERENCE 127

ANNEX..... 131

LIST OF FIGURES

Figure 2.1: CFSTs with different shapes (Han et al., 2014) 8
Figure 2.2: Comparison of compression capacity among materials (Han et al., 2014) 8
Figure 2.3: Comparison of results (Han et al.,2011) 11
Figure 2.4: (a) & (b) - Typical $N_{t-\varepsilon}$ curves (stress strain curve) 12
Figure 2.5: Relative strength of corroded specimen Han et al. (2011) 15
Figure 2.6: Casting of a column on site and a cross-section of CFST 16
Figure 2.7: Different truss types used for the bridges (Miss, n.d.) 17
Figure 2.8: Truss types according to deck location. (A) Deck truss. (B) Half-through truss. (C) Through truss (Weiwei L., 2017) 17
Figure 2.9: Different truss bridges in Sri Lanka 18
Figure 2.10: Force distribution of a truss bridge 19
Figure 2.11: Side view and end condition details of the truss (Fong et. al, 2011) 20
Figure 2.12: Load vs. deflection curve (Fong et. al, 2011) 20
Figure 2.13: Arch bridges constructed in China 22
Figure 2.14: Rectangular and square sections design details (EN 1994-1-1) 23
Figure 2.15 Stress-strain curve 26
Figure 2.16 Drucker-Prager yield criterion 27
Figure 2.17 Finite element model and mesh details (Hu et al., 2011) 29
Figure 2.18: Axial strain vs.axial force (Hibbitt et. al., 2000) 31
Figure 2.19: Finite element details and P (FEM)/ P(test) vs D/t graph 32
Figure 2.20: Stress-strain curves of concrete and steel (Hu et al., 2011) 33

Figure 3.1: School children crossing over a river 37
Figure 3.2: Carrying a dead body across a river 37
Figure 3.3: Crossing the river using a boat 37
Figure 3.4: Old pedestrian bridge in poor condition in Kothmale 39
Figure 3.5: Variable height Gangasiriya Bridge 40

Figure 3.6: Broken old bridge parts used by villagers to cross the river in Lankagama 40
Figure 3.7 Different truss types (Baskaran *et.al.,* 2011) 43
Figure 3.8: Span vs. tonnage graphs for different truss types (Baskaran *et.al,*2011) 44
Figure 3.9: Minimum headroom requirement (Keil, 2013) 46
Figure 3.10: FE model of a Pratt truss (Baskaran et al., 2011) 47
Figure 3.11: Span vs.tonnage graphs for Modified Warren truss type 50
Figure 3.12: Span vs.tonnage graphs for Pratt truss type 50
Figure 3.13: Span vs.tonnage graphs for Parker truss type 51
Figure 3.14: Span vs.tonnage graphs for three trusses 51
Figure 3.15: Parts of the old bridge under existing Ehalakanda Bridge 53
Figure 3.16: Failed Ehalakanda Bridge when launching 54

Figure 4.1: Compressive load test of hollow GI section (1.5 m high, 1.2 mm thick) 58
Figure 4.2: Compressive load test of CFST grade 40 section (1.5 m high, 1.2 mm thick) 58
Figure 4.3: Failure modes of the 1 m height hollow specimens 63
Figure 4.4: Failure modes of the 1.5 m height hollow specimens 64
Figure 4.5: Failure modes of the 1 m height CFST 65
Figure 4.6: Failure modes of the 1.5 m height CFST 66
Figure 4.7: Comparison of experimental and theoretical failure loads of the 1 m height specimens 70
Figure 4.8: Comparison of experimental and theoretical failure loads of the 1.5 m height specimens 70

Figure 5.1: Dimensions of the selected truss bridge for testing ……74
Figure 5.2: Aluminum cross-section details 75

Figure 5.3: Cross-section dimensions 75
Figure 5.4: Compression members which are prone to fail in buckling 76
Figure 5.5: Dimensions of tested specimens (in mm) 76
Figure 5.6: Hounsfield Tensiometer 76
Figure 5.7: Testing of individual members of model trusses 77
Figure 5.8: Samples of Aluminium specimens after testing 79
Figure 5.9: Compressive strength of individual Aluminum members 81
Figure 5.10: Side view of the bridge model 82
Figure 5.11: Sectional view of the bridge model 83
Figure 5.12: Concrete grout infilled members in truss B 83
Figure 5.13: Axial force diagram of Truss A at the theoritical failure load of 2.98 kN 84
Figure 5.14: Axial force diagram of Truss B at the theoritical failure load of 3.81 kN 85
Figure 5.15: Support conditions of tested trusses 86
Figure 5.16: Loading sequnce 86
Figure 5.17: Loading of truss bridge in the laborotary 87
Figure 5.18: Dial gauge setup 87
Figure 5.19: Failure mode of truss A 88
Figure 5.20: Failure mode of truss B 88
Figure 5.21: Initiating point of the crack of truss A 89
Figure 5.22: Initiating point of failure for the truss B 89
Figure 5.23: Comparison of failure modes of truss A and B 89
Figure 5.24: Load vs. Deflection curves obtained for different dial gauges for truss A 91
Figure 5.25: Load vs. Deflection curves obtained from different dial gauges for truss B 92
Figure 5.26: Axial force diagram of Truss A at experimental failure load of 4.25 kN 93
Figure 5.27: Axial force diagram of Truss B at experimental failure load of 5.04 kN 93

Figure 6.1: Response of concrete to uniaxial loading in compression and tension 112
Figure 6.2: Modified Compressive stress-strain model for ABAQUS 114
Figure 6.3: Modified Tension stiffening model for ABAQUS 103
Figure 6.4: Failure modes of the Class 4 hollow GI sections (local buckling) as seen from numerical analysis 105
Figure 6.5: Comparison of failure modes of hollow GI sections (1.2 mm thick) between experimental and numerical results 106
Figure 6.6: Comparison of failure modes of hollow GI sections between experimental and numerical results 106
Figure 6.7: Comparison of failure modes of CFST specimens between experimental and numerical results 107

Figure 7.1: Developed FE Models of the selected truss bridges 112
Figure 7.2: Members replaced with CFST in different truss types 114

LIST OF TABLES

Table 2.1: Dimensions of the specimens 34
Table 2.2 Capacity of specimens for different steel types and thicknesses ... 34

Table 3.1: Pedestrian bridge design details according to different standards (Keil, 2013) 46
Table 3.2: Steel tonnage reduction for each truss type 52
Table 3.3: Average steel tonnage reduction 52

Table 4.1: Theoretical failure loads and modes of the hollow GI specimens 60
Table 4.2: Theoretical failure loads and modes of the CFST 61
Table 4.3: Experimental failure loads and modes of the hollow GI specimens. 62
Table 4.4: Experimental failure loads and modes of the CFST 63
Table 4.5: Comparison of the failure loads obtained for the hollow GI specimens…….....66
Table 4.6: Comparison of the failure loads obtained for the CFST……...68
Table 4.7: Comparison of the improvement in the theoretical failure loads of the CFST compared to hollow GI tubes..... 70
Table 4.8: Comparison of the improvement in the experimental failure loads of the CFST compared to hollow GI tubes..... 71

Table 5.1: Theoretical failure loads and modes of the Aluminium hollow and GFAT 78
Table 5.2: A summary of the failure loads and modes of Aluminium hollow and GFAT 99
Table 5.3: Comparison of experimental failure loads with those obtained from the Theoritical calculations 80
Table 5.4: Comparison of strength enhancement GFAT compared to Aluminium hollow sections 81

Table 5.5: Comparison of theoretical and experimental failure loads of the trusses 94
Table 5.6: Comparison of failure loads between truss A and B 95

Table 6.1: Propertise of self compacting grade 40 concrete 98
Table 6.2: Mechanical properties of grade 40 concrete (Sümer & Aktaş, 2015) 98
Table 6.3: Theoretically obtained Compressive parameters using Wahalathantri's model (Wahalathathri et.al, 2011) 102
Table 6.4: Theoretically obtained Tensile parameters using Wahalathantri's model (Wahalathanthri et.al, 2011) 103
Table 6.5: Failure loads and failure modes of the specimens obtained from numerical analysis using the ABAQUS CAE software 108
Table 6.6: Comparision of failure loads obtained from numerical analysis with those obtained from experiment and Theoretical values 109

Table 7.1: Details of selected truss truss models 111
Table 7.2: Details of the truss members 115
Table 7.3: Deflection in each truss 116
Table 7.4: Steel and concrete tonnage for 8 cases of truss analysis 119

LIST OF ABBREVIATIONS

Abbreviation	Description
CFST	Concrete Filled Steel Tubes
GI	Galvanised Iron
LB	Local Buckling
GB	Global Buckling
CF	Compression Failure
FEM	Finite Element Model
K_t	Tensile strength factor
N_{tu}	Tensile strength of tested CFST specimens
f_y	Yield strength of steel
A_s	Cross-sectional area of the steel tube
E_s	Elastic modulus of steel
E_c	Elastic modulus of concrete
A_s	Cross-sectional area of concrete
N_1	Applied axial force during corrosion stage
ρ_s	Ratio of reinforcement area to concrete area
δ	Steel contribution ratio
$N_{pl,Rd}$	Design plastic resistance
f'_{cc}	Maximum concrete stress
J	Second stress invariant of the stress deviator tensor
GFAT	Grout filled Aluminium Tubes