भारतीय
प्रौद्योगिकी
संस्थान
काशी हिन्दू विश्वविद्यालय

IIT

INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY

CERTIFICATE

It is certified that the work contained in the thesis titled ***"Composite open web steel girder bridge with RCC deck"*** by Mr. Abhishek Sharma (Roll No. 16061001), in partial fulfilment of the requirement for award of degree of Doctor of Philosophy at Indian Institute of Technology (B.H.U) Varanasi, is a record of his own work carried out by under my supervision and guidance and that this work has not been submitted elsewhere for a degree. It is further certified that the student has fulfilled all the requirements of Comprehensive, Candidacy and SOTA.

Signature:

Supervisor
(Prof. Krishna Kant Pathak)

Professor
Department of Civil Engineering
Indian Institute of Technology
(Banaras Hindu University)
Varanasi (U.P.)-221005

भारतीय
प्रौद्योगिकी
संस्थान
काशी हिन्दू विश्वविद्यालय
IIT
INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY

DECLARATION BY THE CANDIDATE

I, Abhishek Sharma (Roll No. 16061001), certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of ***Prof. Krishna Kant Pathak*** from 2016 to 2021, at the ***Department of Civil Engineering,*** Indian Institute of Technology, Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Date: 27-09-2021
Place: Varanasi

Signature of Student
(Abhishek Sharma)

CERTIFICATE BY THE SUPERVISORS

It is certified that the above statement made by the student is correct to the best of our knowledge.

KrishnaKant
Supervisor
Prof. Krishna Kant Pathak
Professor

Signature of Head of Department

विभागाध्यक्ष/HEAD
जानपद अभियांत्रिकी विभाग
Department of Civil Engineering
भारतीय प्रौद्योगिकी संस्थान (का.हि.वि.)
Indian Institute of Technology,(BHU)
वाराणसी-221005/Varanasi-221005

भारतीय प्रौद्योगिकी संस्थान
काशी हिन्दू विश्वविद्यालय
IIT
INDIAN INSTITUTE OF TECHNOLOGY
BANARAS HINDU UNIVERSITY

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: **Composite open web steel girder bridge with RCC deck**

Name of the Student: **Abhishek Sharma**

Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the ward of the Doctor of Philosophy.

Date: 27-09-2021 Signature of Student

Place: Varanasi (Abhishek Sharma)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

Acknowledgement

I express my sincere gratitude and indebtedness to my research supervisor ***Prof. Krishna Kant Pathak,*** Department of Civil Engineering, Indian Institute of Technology (Banaras Hindu University) for his valuable guidance, encouragement and help throughout the tenure of this research work. I am extremely grateful to him for his keen interest in the investigation and the academic help. In course of time, he motivated, inspired and extended the necessary academic help in carrying out my research work. In spite of his busy schedule, he participated in each minute details of my progress of work and shared my pleasures and anxieties as well on the research findings.

I am immensely rejoiced to owe my deep sense of gratitude to Prof. Pramod Kumar Singh, Prof. V. Kumar, Prof. S.B. Dwivedi, Prof. Anil Aggarwal, Prof. S Mandal, Prof. Rajesh Kumar, Dr. P.R. Maiti, Dr. Rosalin Sahoo and Dr. Brind Kumar for their constant encouragement during research work. I am thankful to Prof. Prabhat Kumar Singh Dikshit, Head, Department of Civil Engineering, for giving me all the facility during my research work.

I am thankful to all non-teaching staff members especially lab attendants of structural laboratory of the Department of Civil Engineering for their kind cooperation and inspiration. I wish to express my deep gratitude to all those who have extended their helping hands in various ways during my tenure at Indian Institute of Technology (Banaras Hindu University), Varanasi, India.

Date: 27-09-2021
Place: Varanasi
Abhishek Sharma

TABLE OF CONTENT

Certificate i

Declaration by the candidate ii

Copyright transfer certificate iii

Acknowledgement iv

Table of Contents v

List of Figures viii

List of Tables xii

Preface xiii

Chapter 1 INTRODUCTION **Page No.**

1.1 General 1

1.2 Analysis of failure of bridges 3

1.3 Composite construction 5

1.4 Scope of present study 8

1.5 Layout and contribution of thesis 9

Chapter 2 LITERATURE REVIEW **11**

2.1 General 11

2.2 Brief history of failure of bridges 11

2.3 Significant failure of bridges due to buckling 17

- 2.3.1 Brief history of I-35W bridge 17
- 2.3.2 Failure of under-construction Chauras bridge 19

2.4 Developments in composite open web steel girder technology 21

2.5 Laboratory experiments for analysis of composite action 25

- 2.5.1 Composite open web steel girder bridge 25
- 2.5.2 Composite steel and concrete bridge trusses 28

2.6 Composite open web steel girder bridge 31

2.7 Shear connections in composite truss bridges 41

2.8 Behaviour of shear connectors 46

- 2.8.1 Mechanism of flexible shear connectors 47
- 2.8.2 Longitudinal shear low in solid and open web steel girder bridges 48

2.9 Codal provisions for shear connectors 49
  2.9.1 Indian code provisions 49
  2.9.2 Canadian code provisions 51
  2.9.3 American code provisions 52
  2.9.4 Euro code provisions 53
2.10 Literature survey 53

Chapter 3 EXPERIMENTAL DETAILS AND RESULTS 55
3.1 Buckling in steel truss bridge 56
3.2 Material tests 58
  3.2.1 Tensile test of 8.0mm x 8.0mm bar 59
  3.2.2 Compression Test 63
3.3 Model design and fabrication 66
  3.3.1 Design of joints 67
  3.3.2 Deign of supports 69
3.4 Load test of non-composite model 71
3.5 Load test of composite model 77
  3.5.1 Model preparation 77
  3.5.2 Design of shear studs 78
  3.5.3 Fabrication of Composite model 81
  3.5.4 Experimental Setup 84
  3.5.5 Composite model test results 86

Chapter 4 NUMERICAL ANALYSIS AND DISCUSSION 97
4.1 Numerical analysis of Models 97
  4.1.1 Non-Composite Models 97
  4.1.2 Composite Model 98
4.2 Effect of shrinkage strain 100
4.3 Discussion 106
  4.3.1 Validation of the STAAD results 106
  4.3.2 Load-deflection relationship 110
  4.3.3 Load carrying capacity 111
  4.3.4 Stiffness 111

4.3.5 Mode of Failure 112

4.3.6 Load sharing between steel top chord and the RCC deck slab 112

4.3.7 Performance of shear studs 114

Chapter 5 NUMERICAL COMPARISON BETWEEN THROUGH TYPE AND DECK TYPE TRUSS BRIDGES WITH COMPOSITE AND NON-COMPOSITE DECKS 117

5.1 General 117

5.2 Geometrical details of the bridges 118

5.3 Analysis of the bridges 124

5.3.1 Modelling 124

5.3.2 Loading 124

5.4 Numerical Comparison of bridges 128

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS 137

6.1 General 137

6.2 Future Scope of Study 141

References 143

Annexure A 149

Annexure B 150

Annexure C 158

Annexure D 161

List of Publications 165

LIST OF FIGURES

Figure No.	Figure Caption	Page No.
Figure 1.1	Typical cross sections of through and deck type bridges	2
Figure 1.2	Failed Chauras Bridge during casting of deck slab	5
Figure 1.3	Composite deck type steel open web girder bridge	7
Figure 2.1	Failure causes and mode of failure leading to collapse	12
Figure 2.2	Distribution of failed bridges in India from 1977 to 2017	14
Figure 2.3	Causes of bridge failure in India	15
Figure 2.4	Component wise failure of bridges in India	16
Figure 2.5	Yearly distribution of failed bridges	16
Figure 2.6	Distribution of failed bridges as per their age	17
Figure 2.7	Failed superstructure of I-35W bridge	18
Figure 2.8	Failed gusset plate at U10 joint	19
Figure 2.9	Failed Chauras bridge during concreting	20
Figure 2.10	Member stresses at the time of the collapse	20
Figure 2.11	Buckled member U13U14	21
Figure 2.12	Truss arrangement and member dimensions for the test model	26
Figure 2.13	Stress-displacement variation or the steel members and Reinforcement	27
Figure 2.14	Load-displacement relation for (a) middle section (b) end section	28
Figure 2.15	Truss arrangement for experimental study	29
Figure 2.16	Stress-strain relation for the materials used	30
Figure 2.17	Comparison of Eurocode 4 results with analytical results	30
Figure 2.18	Simply supported composite truss bridge of span 36m	33
Figure 2.19	General view of the Lully viaduct composite bridge	34
Figure 2.20	Longitudnal view and standard cross-section	35
Figure 2.21	K-shaped joint geometry with shear studs	35
Figure 2.22	Bogibeel bridge	36
Figure 2.23	View of Ulla river viaduct	37
Figure 2.24	Sarutagawa bridge	38
Figure 2.25	Composite construction with prestressing of upper and lower slabs	39
Figure 2.26	Rigid connectors	42
Figure 2.27	Flexible connectors	43

Figure 2.28 Anchorage shear connectors 43
Figure 2.29 Headed shear connectors 44
Figure 2.30 Non-composite and composite beams 46
Figure 2.31 Mechanism of shear force distribution for stud type shear Connector 47
Figure 2.32 Shear flow in shear connectors 48
Figure 2.33 Densification of shear connectors 49
Figure 3.1 Kotibhel bridge (30 m span) 58
Figure 3.2 Mounting of extensometer and 120 Ω and 350 Ω strain gauges 60
Figure 3.3 Stress-strain curves of 8 mm x 8 mm square bar 62
Figure 3.4 Dimension of sample for compression test 64
Figure 3.5 Test sample (a) Initial (b) Failed 64
Figure 3.6 Stress-strain curve for the compression test 65
Figure 3.7 Stress-strain curves for tension and compression 65
Figure 3.8 Model details (a) Dimensions (b) 3-D view 66
Figure 3.9 Member forces under joint loads P 67
Figure 3.10 Plates and weld dimensions for joint E and D 69
Figure 3.11 Arrangement of the moel above the supports 71
Figure 3.12 (a) Model just beore failure (b) Model after sudden top chord buckling failure 72
Figure 3.13 Strain recorded from strain gauges 73
Figure 3.14 Stress- average recorded strain variation 74
Figure 3.15 Load deflection curves from the two dial gauges attached To the bottom chord of non-composite model 76
Figure 3.16 Average of experimentally observed and analytically Observed vertical deflection for the non-composite model 76
Figure 3.17 Deck slab on 42 m span open web steel girder bridge on Devidhar fold to Bhatwadi-Panchangaon road at Uttrakhand 78
Figure 3.18 Shear studs and deck reinforcement 82
Figure 3.19 Inverted model in the mould for deck slab curing 83
Figure 3.20 Deck slab before and after plastering 83
Figure 3.21 Finished model 84
Figure 3.22 Setup for the composite model test, showing UTM, data logger And mounted strain gauges 85

Figure 3.23 a) 2 number 120-ohm strain gauges mounted on each steel Member at top and bottom chords. (b) 5 number 350-ohm strain gauges at 6.5 cm c/c mounted of the deck slab 86
Figure 3.24 Model (a) before failure (b) after failure due to rupture of the bottom chords 87
Figure 3.25 Bottom chord rupture at failure 88
Figure 3.26 Deck slab top view after failure 88
Figure 3.27 Load (kN) – strain curves for the four strain gauges pasted on the top members (Strain gauge number: 1,3,5,7) 90
Figure 3.28 Load (kN) – strain curves for the four strain gauges pasted on the bottom members (Strain gauge number: 2,4,6,8) 90
Figure 3.29 Deck slab strain profiles at different loadings 92
Figure 3.30 Stress in deck slabs as per STAAD analysis at 3 t load 92
Figure 3.31 **C**omparison of recorded strain in deck slab and strain as per STAAD analysis 93
Figure 3.32 Average load – strain curves for top and bottom chords, and The deck slab at truss locations 94
Figure 3.33 Load-deflection curves for dial gauges 1 and 2 for the composite Model 95
Figure 3.34 Average experimental deflection for the composite model, and corresponding STAAD deflection 96
Figure 4.1 Variation of vertical deflection as obtained from various grid Sizes of STAAD and experimental deflection 98
Figure 4.2 Meshing of the deck slab 99
Figure 4.3 Vertical deflections of the truss 99
Figure 4.4 Strain Diagram 102
Figure 4.5 Elevation of 30 m span bridge used for analysis 103
Figure 4.6 Stress contour of 30 m span bridge analysed for live load Condition in STAAD.Pro 103
Figure 4.7 Elevation of 42m span bridge 104
Figure 4.8 Deck slab stress under LL alone 104
Figure 4.9 Loading arrangement for fully loaded deck slab 105
Figure 4.10 Strain in the bottom chord 107
Figure 4.11 Strain in the steel top chord 108

Figure 4.12 Deflection of the bridge model 108
Figure 4.13 Variation of deck slab strain 110
Figure 4.14 Load-deflection relationship for composite and non-composite Models 111
Figure 4.15 Load sharing between top chord, bottom chord, reinforcement And concrete deck 114
Figure 4.16 Variation of shear force (kN) in shear studs as per STAAD 115
Figure 5.1 Bridge system (a) Through type bridge (b) Deck type bridge 117
Figure 5.2 Bridge configuration (a) Through type bridge (b) Deck type bridge 120
Figure 5.3 STAAD model for through type and deck type 60 m span bridge 124

LIST OF TABLES

Table No.	Table Caption	Page No.
Table 3.1	Effective length of compression members	57
Table 3.2	Applied loads and recorded strains	61
Table 3.3	Material properties of 8 mm square bar	62
Table 3.4	Strain from the compression test	63
Table 3.5	Strain measured using strain gauges	72
Table 3.6	Vertical deflection of the non-composite model	75
Table 3.7	Shear studs analysis	79
Table 3.8	Spacing and number of studs	81
Table 3.9	Deck concrete cube test results	84
Table 3.10	Classification of strain gauges mounted on members	86
Table 3.11	Load versus recorded strain data for members	89
Table 3.12	Strain recorded in deck slab	91
Table 3.13	Vertical deflection of the composite model	95
Table 5.1	Cross-sections used in modelling of 60 m span bridges	121
Table 5.2	Primary loads	125
Table 5.3	Load for class A vehicle	126
Table 5.4	Calculation of wind load	127
Table 5.5	Member stresses for non-composite deck type bridge	129
Table 5.6	Member stresses for composite deck type bridge	130
Table 5.7	Member stresses for non-composite through type bridge	130
Table 5.8	Member stresses for composite through type bridge	131
Table 5.9	Maximum stresses at member locations for deck type bridges	132
Table 5.10	Maximum stresses at member locations for through type bridges	132
Table 5.11	Deflection obtained from analysis	133

PREFACE

In the past, several steel open web girder bridges have failed during various stages of construction or in-service conditions. Sudden failure or collapse of the bridge is always a catastrophic disaster, as such a type of collapse does not give any precautionary warning. The possibility of a sudden collapse of truss bridges has always been due to the buckling of non-redundant critical compression members. Unlike compression members, tension members do not usually fail suddenly since they experience noticeable elongation and can take stress up to ultimate stress beyond the yield stress. One way to avoid buckling is to provide a composite RCC deck with the compression members. The use of composite RCC decks in steel bridges is now increasing. A detailed experimental study was conducted to ascertain improvements due to composite RCC deck over non-composite bridge model. Deck-type steel bridge models, with and without composite decks were tested in the laboratory up to failure. The failure in the non-composite model was observed due to buckling of the top chord member at a stress of 234.6 N/mm^2, whereas for the model with the composite deck it changed to rupture of the bottom chord in tension at a stress of 614.8 N/mm^2. The failure load and stiffness of the structure also increased significantly due to the composite action. Shear connectors designed as per IRC 22:2015 transferred the shear effectively and the deck slab participated in load sharing. Further, load sharing in the top chord compression member comprising the steel top chord, the concrete in the deck slab, and the reinforcing steel in it, was also explored. It is found that 72.0% of the composite top chord compressive force is taken by the RCC deck, and in the RCC deck, 30.7% force is taken by the reinforcement. Strain variation in deck slab was also recorded using strain gauges. Strain in deck slab over top chord members was observed to be 54% more than the strain in the middle of the deck slab.

In the literature, detailed provisions for the analysis and design of steel and RCC deck composite open web steel girder bridges do not exist. The model on which the experiment is performed is modelled on STAAD Pro. v8i software. The experimental test results are used to validate the STAAD analysis results. Bottom chord strain and mid-span deflection of the composite bridge model as found from the STAAD analysis and the laboratory experiment closely tally with each other. This validates the standard STAAD analysis results. However, in the top chord member, due to shrinkage cracks in the deck slab concrete and deformation in shear connectors, the experimentally recorded strain is higher by about 100% than the STAAD analysis result. Shear force in studs is considerably large near supports and joints as compared to the midsection. Therefore, the design of shear studs may be carried out based on the shear forces in the studs found from the STAAD analysis. Thus it is recommended that STAAD or any other standard finite element analysis software can be used for the analysis and design of the composite bridges.

Moreover, the impact of a composite deck is also studied for through type and deck type truss bridges. In trusses, deck type and through type truss systems are generally provided with various member arrangements. To study the effectiveness of composite deck with through type and deck Type Bridge, analysis of 60.0 m deck type and through type, non-composite and composite bridges are done. The bridges are modelled using STAAD. Pro v8i software with truss members as beam element and deck slab modelled as four nodded plate element. The loading on the bridge is done as per the provisions of IRC 6:2017 and IRC 24:2010. The composite deck decreases vertical stiffness and increases the stiffness of the bridge. The composite deck effectively reduces the horizontal deflections due to lateral seismic and wind loads in both the truss systems. Stresses in the members made composite with the deck slab were also reduced and hence may result in material saving and decreased steel offtake. In the case of composite deck-type bridges due to load sharing by the deck slab, the stresses in the top chord are reduced significantly hence eliminating the chances of buckling. Advantages of the composite deck are better utilized in deck type bridge system compared to through type bridge system.