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STATE OF ART ON STEEL – TIMBER – (CONCRETE) STRUCTURES

Technical Working Group 11.6
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Interim Report of ECCS TC11/WG6: Steel-Timber Hybrid Structures

State of art on Steel-Timber-(Concrete) Structures

1st Edition, 2024

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PREFACE

This document intends to provide guidance on the available research in the open literature related to steel timber composite structural elements.
The document starts with an overview of the wood classification and strength classes of sawn timber as well as their mechanical properties and behaviour. In addition, a description of some engineered timber products is included together with relevant properties. A comprehensive state of art is provided furthermore in order to identify the main lacks and is divided into 9 distinct items: timber material and products; shear connections; beam-column joints; beams and slabs; columns, walls diaphragms and bracings; fire design and sustainability. The last chapter contains the main conclusions of the extensive state-of-the-art and provides guidance for future research topics.
The content of this document is expected to be a high value to future research topics when dealing with steel timber composite and hybrid actions. The information present in the Items will be a basis for the future design guidelines and background document for the next generation of design guide for steel timber composite and hybrid structural elements.
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SYMBOLOGY

Abbreviations

STC – Steel-timber composite
SCT – Steel concrete composite
CLT – Cross laminated timber
LVL – Laminated veneer lumber
PSL – Parallel strand lumber
LSL – Laminated strand lumber
OSB – Oriented strand board
RBS – Reduced beam section
T-BRB – Timber buckling-restrained brace
STC – Steel-timber composite
RL – Radial-longitudinal
σ – Stress
Ɛ – Strain
k_{mod} – Reduction coefficient
k_{def} – Deflection coefficient
Glulam – Glued laminated timber
GL_{xxh} – Homogeneous glulam
GL_{xxc} – Composite glulam
$f_{m,g,k}$ – Bending strength
$f_{t,0,g,k}$ – Tension strength
$f_{t,90,g,k}$ – Tension strength
$f_{c,0,g,k}$ – Compression strength
$f_{c,90,g,k}$ – Compression strength
$f_{v,g,k}$ – Shear strength
$E_{0,g,mean}$ – Modulus of elasticity
$E_{0,g,05}$ – Modulus of elasticity
$E_{90,g,mean}$ – Modulus of elasticity
$G_{g,mean}$ – Shear modulus
$\rho_{g,k}$ – Density
$f_{m,x,k}$ – Bending strength
$f_{m,y,k}$ – Bending strength
$f_{t,0,x,k}$ – Tension strength
$f_{t,0,y,k}$ – Tension strength
$f_{t,90,x,k}$ – Perpendicular tension strength
$f_{t,90,y,k}$ – Perpendicular tension strength
$f_{c,0,x,k}$ – Compression strength
$f_{c,0,y,k}$ – Compression strength
$f_{c,90,z,k}$ – Perpendicular compression strength
$f_{v,090,xlay,k}$ – Longitudinal shear strength
$f_{v,090,ylay,k}$ – Longitudinal shear strength
$f_{v,9090,xlay,k}$ – Rolling shear strength
$f_{v,9090,ylay,k}$ – Rolling shear strength
$E_{0,x,mean}$ – Mean value of modulus of elasticity
$E_{90,x,mean}$ – Mean value of modulus of elasticity
$E_{0,y,mean}$ – Mean value of modulus of elasticity
$E_{90,y,mean}$ – Mean value of modulus of elasticity
$E_{0,x,05}$ – Fifth percentile value of modulus of elasticity
$E_{0,y,05}$ – Fifth percentile value of modulus of elasticity
$G_{090,xlay,mean}$ – Mean value of modulus of shear
$G_{090,ylay,mean}$ – Mean value of modulus of shear
$G_{9090,xlay,mean}$ – Mean value of modulus of rolling shear
$G_{9090,ylay,mean}$ – Mean value of modulus of rolling shear
$\rho_{xlam,k}$ – Characteristic value
$\rho_{xlam,mean}$ – Mean value
GLVL – Glued laminated veneer lumber
PU – Phenol formaldehyde
MUF – Melamine formaldehyde
PRF – Phenol resorcinol formaldehyde
$f_{m,0,edge,k}$ – Bending strength parallel to grain edgewise
$f_{m,0,flat,k}$ – Bending strength parallel to grain flatwise

s – Bending strength size effect parameter
$f_{t,0,k}$ – Tension strength parallel to grain
$f_{t,90,edge,k}$ – Tension strength perpendicular to grain edgewise
$f_{c,0,k}$ – Compression strength parallel to grain for service
$f_{c,90,edge,k}$ – Compression strength perpendicular to grain edgewise
$f_{c,90,flat,k}$ – Compression strength perpendicular to grain flatwise
$f_{c,90,flat,k,pine}$ – Compression strength perpendicular to grain flatwise pine
$f_{v,0,edge,k}$ – Shear strength parallel to grain edgewise
$f_{v,0,flat,k}$ – Shear strength parallel to grain flatwise
$E_{0,mean}{}^{e}$ – Modulus of elasticity parallel to grain
$E_{0,k}{}^{f}$ – Modulus of elasticity parallel to grain
$E_{c,90,edge,mean}{}^{g}$ – Modulus of elasticity parallel to grain edgewise
$E_{c,90,edge,k}{}^{h}$ – Modulus of elasticity parallel to grain edgewise
$G_{0,edge,mean}$ – Shear modulus parallel to grain edgewise
$G_{0,edge,k}$ – Shear modulus parallel to grain edgewise
$G_{0,flat,mean}$ – Shear modulus parallel to grain flatwise
$G_{0,flat,k}$ – Shear modulus parallel to grain flatwise
ρ_{mean} – Density mean value
ρ_{k} – Density characteristic value
$f_{m,90,flat,k}$ – Bending strength perpendicular to grain flatwise
$f_{v,90,flat,k}$ – Shear strength perpendicular to grain flatwise
$E_{c,90,edge,mean}{}^{f}$ – Modulus of elasticity perpendicular to grain edgewise
$E_{c,90,edge,k}{}^{k}$ – Modulus of elasticity perpendicular to grain edgewise
$E_{m,90,flat,mean}$ – Modulus of elasticity perpendicular to grain flatwise
$E_{m,90,flat,k}$ – Modulus of elasticity perpendicular to grain flatwise
$G_{90,flat,mean}$ – Shear modulus perpendicular to grain flatwise
$G_{90,flat,k}$ – Shear modulus perpendicular to grain flatwise
l/d – Length to diameter ration
d_s – Fastener diameter
t_s – Flange thickness
FE – Finite element
BCGP – Cementitious grout
L_s – Shank length
f_y – Steel yield strength
G/T – Grout strength to timber strength ratio
W – Width of the pocket
HSFG bolts – High strength friction grip bolts
SCT – Shear connection type
P_{SC} – Peak load
P_{ST} – Peak load
δ_{SC} – Small slip
δ_{ST} – Significant slip
AISC – American Institution of Steel Construction
EWP – Engineered wood product
M_u – Ultimate bending moment
$S_{j,ini}$ – Initial rotational stiffness
θ_u – Rotation capacity
M – Bending moment
θ – Joint rotation
UMAT – User-defined material
μ – Friction coefficient
$M_{j,r}$ – Bending moment resistance

F_i – Component row
z – Level arm
F_t – Maximum loading capacity
$F_{b(i)}$ – Shear force
Δ – Deviation parameter
FEM – Finite element model
CDM – Continuum damage model
k_i – Initial stiffness
k_p – Hardening stiffness
M_o – Reference bending moment
$M_{j,y}$ – Yield bending moment
SHS – Square hollow section
SVD-AUKF – Singular value decomposition into an adaptive unscented kalman filter
MRF – Moment resisting frame
LVDT – Linear variable displacement transducer
M-θ – Bending moment rotation
CR – Capacity ratio
CR-S_{ini} – Initial stiffness
CR-F_y – Yielding strength
CR-D – Ductility
P_Y – Yielding of link
P_P – Plasticization of link
P_C – Link ultimate strength
$M_{i,Rd}$ – Bending resistance
OS_i – Overstrength
$M_{l,pl,Rd}$ – Bending design resistance
STS – Self-tapping screws
SCC – Self-compacting concrete
CFS steel – Cold formed steel
LTB – Lateral torsional buckling
SPF – Spruce-pine-fir
Prefa-SeTi – Steel-timber composite beam
FNR – National research fund
ULS – Ultimate limit state
SLS – Serviceability limit state
WQ beam – Welded box steel slim-floor beam
FRP – Fibre plastic polymers
CHS – Cylindrical hollow sections
CFRP – Carbon fibre reinforced polymer
RHS – Rectangular hollow steel
PLW – Peak load to weight ratio
TFST – Timber-filled steel tubular
MoE – Modulus of elasticity
CFST – Concrete-filled steel tubular
TFGT – Timber filled pultruded GFRP tube
GFRP – Fiber-reinforced polymer
L-STC – L-shaped steel-timber column
PU – Polyurethane
FFTT – Finding the forest through the trees
EVD – Equivalent viscous damping
SMRF – Steel moment-resisting frame
DDBD – Direct displacement-based design
RSM – Response surface method
ANN – Artificial neural network
MISD – Maximum inter-story drift
RISD – Residual inter-story drift
GP – Gaussian process
ACMR – Adjusted collapse margin ratio
SC-RW – Self-centring rocking wall
RSF – Resilient slip friction
SMF – Steel moment frame
IO – Immediate occupancy
CP – Collapse prevention
IDA – Incremental dynamic analysis
PT – Post-tensioned
GWB – Gypsum-based wallboard
RCf – Reinforced concrete floor
CLTf – CLT floor
CFD – Computational fluid dynamics
FDS – Fire dynamics simulator

SB – Swage beam
NBCC – National building code of Canada
DBE – Design based earthquake
MCE – Maximum considered earthquake
ADAS – Additional damping and stiffness
GIR – Glued-in rod
UFP – U-shaped flexural plate
V-CBF – V-configuration concentric bracing frame
X-CBF – X-configuration concentric bracing frame
D-CBF – Diagonal-configuration concentric bracing frame
EBF – Eccentric bracing frame
DCM – Dissipative structural behaviour
DLS – Damage limitation state
LS – Life safety
CM – Collapse mechanism
SGLRS – Separated gravity and lateral resisting system
SPSW – Steel plate shear wall
NGA – Next generation attenuation
CDF– Cumulative distribution function
9D – 9-story structure with deformable connection
9R – 9-story structure with rigid connection
HT-BRBF – Heavy timber buckling-restrained braced frame
β – Damping value
T – Building period
A – Floor acceleration
f_0 – Frequency
MPP – Mass plywood panel
CA – Casing interface
CO – Core steel
CC – Core-casing interface
η – Constraint ratio
l_f – Fastener spacing
$l_{f,end}$ – Fastener spacing
FEA – Finite element analysis
HRR – Heat release rate
β_n –Notional charring rate
MUF – Melamine-urea-formaldehyde
ITI – Department of structural design and timber engineering
AST – Adiabatic surface temperature
LCA – Life cycle assessment
GWP – Global warming potential
GHG – Greenhouse gases
CO_2eq. – Carbon equivalence
MCI – Material circularity indicator
PCI – Product circularity indicator
BCI – Building circularity indicator
SCI – System circularity indicator
DfDR – Design for disassembly and reuse
BF – Blast furnace
BOF – Blast oxygen furnace
EAF – Electric arc furnace
ECF – Embodied carbon factors
EPD – Environmental product declaration
C1 – Considered product
C2 – End-of-life destination
C3 – Reuse, recovery or recycling
C4 – Disposal
DfD – Design for disassembly and deconstruction
ISO – International Organization for Standardization
CTBUH – Council of Tall Buildings and Urban Habitat
2D – Two-dimensional

3D – Three-dimensional
PEF – Product environmental footprint
CPR – Construction products regulation
LEED – Leadership in energy and environmental design
BREEAM – Building research establishment environmental assessment method
DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen – German Society for Sustainable Building
FSC – Forest stewardship council

CONTENTS

INTRODUCTION

Innovations in timber engineering and constructions, improvements in numerical analysis, structural capability evaluation and experimental tests on timber structural systems and nodal assemblages all around the world have contributed to a rising interest in hybrid steel-timber braced structures. In fact, they are characterized by the intelligent and more efficient use of the two materials to improve the global and local behaviour of all-timber or all-steel structures The benefits of this structural type also involve the design of optimized seismic structures, where lightness of timber is combined with the stiffness and ductility of steel. Nowadays, research into hybrid steel-timber braced structures is still very recent and fairly limited.
Timber is a natural and organic construction material with several attributes. It can be used in hybrid and composite construction with steel and/or concrete and it is a fully renewable and largely recyclable material. Because it is a naturally grown material, timber is a complex building material. Its properties are highly variable and are sensitive to environmental and loading conditions. It is highly anisotropic with high strength and stiffness parallel to the grain but low properties perpendicular to the grain. These factors must be taken into account in the design of timber structures.
Aside from sawn timber, wood is also processed into structurally optimized building materials known as engineered timber. The benefits of these wood composites manufactured from laminated timbers, timber particles, adhesives and other materials, include increased dimensional stability, more homogeneous mechanical properties, and greater durability.

The state-of-the-art findings in this document will serve for future guidance in research topics to help finalize a design guideline for structures having steel timber composite/hybrid structures. These recommendations are summarized in the last chapter and are intended to outline future research subjects and give technical knowledge so that a comprehensive design code for Steel-Timber Composite Structures can be developed. The recommendations are separated into the following subchapters:
ITEM 1 Timber Materials and Products presents an overview of the wood classification, and strength classes of sawn timber as well as their mechanical properties and behaviour. In addition, a description of some engineered timber products is included together with relevant properties.
ITEM 2 Shear Connections is focused on push-out tests with monotonic and cyclic loads and their numerical or analytical analyses. A summary of possible shear connection solutions applicable to steel-timber composite beams is provided, where

key advantages and disadvantages are highlighted. The behaviour of steel-timber shear connectors is also assessed, where current state-of-the-art limitations are debated. In addition, a brief review of steel-timber-concrete floors and the shear connection solutions applicable to such floors is also included.

ITEM 3 Beam Column Joints is focused on connections that are using mainly screws, bolts and a combination of these using epoxy glue. However, there are other custom connections which include threaded rods welded to steel beams, bolts in grout pockets, among others.

ITEM 4 Beams and Slabs presents an overview of steel-timber flooring systems shear connections with different types of screws and bolts. Analytical models have been developed to reproduce the behaviour of the connections tested.

ITEM 5 Columns contains a summary of different studies on stub/slender steel-timber cross-sections obtained by combining the materials, timber-filled steel profiles or steel profiles embedded in timber represent the most popular configurations investigated in the last decade. Two main groups of steel-timber composite columns were experimentally and numerically investigated in the last years, namely timber-infilled and timber-encased steel columns. Although significant knowledge contributions have been made to the field of steel-timber composite columns, extensive studies are yet necessary to ensure a comprehensive understanding of their load-bearing behaviour and to support the development of reliable analytical tools for predicting their behaviour in real applications.

ITEM 6 Walls, Diaphragms and Braces presents an overview of the existing research on Steel-Timber Composite (STC) shear walls and diaphragms, on steel-timber hybrid framed systems and Timber Buckling-Restrained Braces (T-BRB). In particular, the results of the experimental and numerical analysis are presented and discussed in terms of the main structural performance, highlighting the innovations of the systems studied.

ITEM 7 Fire design aims to present an overview of the behaviour of wood products and steel at elevated temperatures, including the relevant thermal and mechanical properties as a function of the temperature. The most relevant investigations and findings on the behaviour of steel-timber structures or structural elements in fire will be presented and discussed, identifying whenever possible existing gaps in knowledge and new research paths. Both prescriptive and performance-based approaches will be considered and discussed.

ITEM 8 Sustainability presents the effect of using different structural systems based on using various materials and their Impact to the CO2 emissions. Circularity and as well sustainability principles are explained in this chapter. several case studies are provided to offer to the reader a better understanding on the Impact of composite steel timber systems.

The American Institute of Steel Construction (AISC) has launched the first design guide containing the first-ever set of recommendations for hybrid steel frames with mass timber floors [2]. However, it is not for steel timber composite structures, but for hybrid steel timber buildings. The design guide provides a context for the new building typology, detailing strategies from the perspective of multiple disciplines. By facilitating this new generation of sustainable buildings, the guide will help accelerate the use of hybrid timber and steel in multi-story residential and commercial construction. Multidisciplinary aspects like structural design, fire safety, acoustic, and sustainability specialists, provide a holistic overview of the design considerations that impact hybrid structures; it demonstrates how safety, structural strength, vibration, and acoustical control can be achieved with this typology by following a holistic design approach.

Lessons learned upon already built steel timber projects, [1] can be resumed as follows:

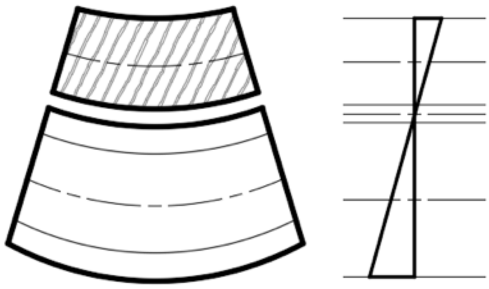
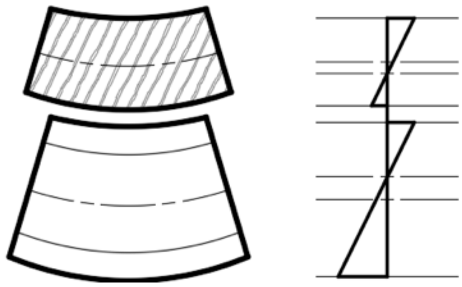
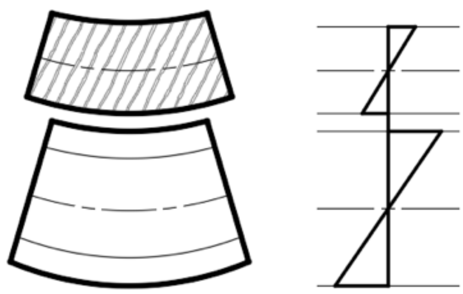
- Connections & material interfaces are critical (careful coordination during design & shop drawings; differences in tolerances; differences in material movements - vertically and horizontally).
- Handle with care (timber is exposed, finish surface; moisture impacts, staining, rust; steel may have a primer or fire coating).
- Logistics are key (ideal to have same installer for timber and steel; delivery & install sequencing – keep tight schedules, may need additional material storage on site; don’t slow down one material’s install speed due to the nature of the other).

TERMINOLOGY

In structural engineering, a system with two or more materials can be called a hybrid. Composite is an action between materials that changes the way that each structural element behaves individually.

Based on the level of interaction and how the load capacity is evaluated, hybrid structures can be either additive or composite systems. Table 0.1 exemplifies these concepts on structural beam elements.

Table 0.1: **Beam structural element – composite /additive and hybrid concept**

<table>
<tr><td rowspan="3">Beam structural element</td><td colspan="2">HYBRID STRUCTURES</td></tr>
<tr><td>COMPOSITE</td><td>ADDITIVE</td></tr>
<tr><td>η = 1

η ≤ 1, η ≥ 0, η ≥ min η
</td><td>2 parts, each working ion its own
η = 0
(at least not considered in the structural design calculation)
</td></tr>
<tr><td>Interaction mode</td><td>Act commonly > ∑ of parts</td><td>Act independently
Act in a chain one after another</td></tr>
<tr><td>Load bearing capacity</td><td>Bigger than the sum of the parts</td><td>The load bearing capacity of the weakest element alone or the sum of parts</td></tr>
</table>