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# HOLISTIC DESIGN OF TALLER TIMBER BUILDINGS – COST ACTION HELEN (CA20139)

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**ABSTRACT:** With the worldwide construction sector being responsible for one third of carbon dioxide emissions, as well as forty percent of the world's energy use and waste production, a shift to sustainable and renewable construction techniques is crucial. Engineered timber, a champion of sustainable construction materials, has evolved to a stage that enables the construction of not only family housing but also taller buildings so far commonly built from concrete or steel. Designing taller timber buildings made is more demanding than their concrete and steel counterparts. Whereas different design aspects (architectural, structural, fire safety, acoustics, etc.) of concrete buildings can work almost independently, the design of taller timber buildings should be performed with intensive collaboration among the design teams. It is therefore crucial to address taller multi-storey timber buildings from a collaborative and interdisciplinary perspective, considering static, dynamic, fire, acoustic, human health, and other aspects in parallel and not in isolation. Only through interdisciplinary analysis and interaction can a set of holistic design guidelines be developed that will enable the safe construction of taller timber buildings, as well as respect human wellbeing demands. In this paper, the COST Action CA20139 will be presented and the main aims will be discussed.

**KEYWORDS:** COST, holistic design, tall timber buildings, sustainability, multi-storey timber, robustness, design for adaptability and reuse, deformation and vibrations, durability, seismic design, fire

## 1 INTRODUCTION

The number and height of multi-storey timber buildings substantially increased over the past decade [1, 2]. The envelope is being pushed every year, and the current record (as of 2020) for a purely timber multi-storey apartment building stands at 18 storeys (85 m), while for a timber-concrete hybrid it stands at 24 storeys (84 m). Hence, timber buildings up to 10 storeys are in the meanwhile already considered as midrise.

Due to targets regarding a more sustainable and healthier environment, contemporary multi-storey timber buildings are being recognised as a long-term sustainable solution, especially in urban areas where they present an environmentally friendly alternative to concrete and steel buildings [3].

The design of taller timber buildings so far has always been made by highly specialised engineering teams that were well aware of the unique demands and challenges that multi-storey timber buildings are associated with. Despite that several midrise and a few taller timber buildings have been already built, the knowledge level as well as the number of recognised experts on taller timber buildings is still far from its concrete and steel counterparts.

Additionally, there are also new and most likely more challenges to be tackled with taller timber buildings [4]. Despite efforts, practically all the worldwide research performed in the field of multi-storey timber buildings was performed partially with intense focus on individual fields (connections, vibrations, acoustics, fire, durability [5-6]) and not considered from a wider perspective, namely in a holistic manner. However, a well-integrated design is absolutely crucial for designing taller timber buildings.

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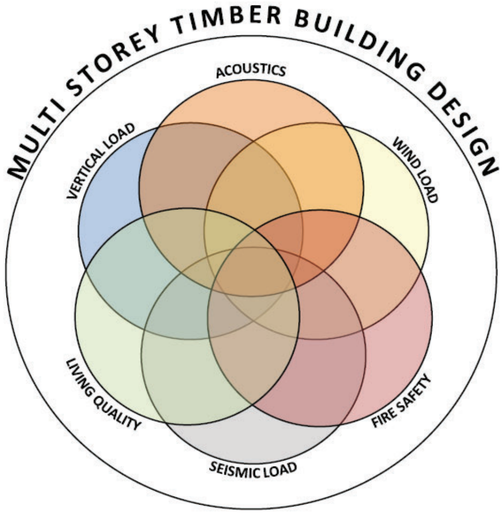


| INTERACTIONS<br>+ positive<br>- negative<br>N neutral | VERTICAL LOAD | WIND LOAD | SEISMIC LOAD | FIRE SAFETY | ACOUSTICS | LIVING QUALITY |
|---|---|---|---|---|---|---|
| VERTICAL LOAD | | + | - | - | + | N |
| WIND LOAD | + | | + | N | - | N |
| SEISMIC LOAD | - | + | | N | - | N |
| FIRE SAFETY | - | N | N | | + | - |
| ACOUSTICS | + | - | - | + | | - |
| LIVING QUALITY | N | N | N | - | - | |

***Figure 1****: Interaction of a few different building design fields and their inherent collisions, either positive or negative, that need to be resolved for multi-storey taller timber buildings.*

## 2 CHALLENGES AND AIMS OF THE COST ACTION

COST Action CA20139 – Holistic design of taller timber buildings (HELEN) was started on 12/10/2021 and runs until 11/10/2025. It will try to change the paradigm of building construction research, shifting R&D from isolated topics to an integrated interdisciplinary approach, which is critically necessary to safely design and build as well as correctly maintain and recycle taller timber buildings. There are several reasons why: less general experience with them; codes for timber buildings are not as developed as they are for concrete or steel [7,8]; and less suitable literature is available for practicing designers. However, a key difference is the design complexity of timber buildings due to basic material properties. Whereas different designers (architects and structural, fire and acoustic engineers) of concrete buildings can work almost independently, the design of taller timber buildings should be performed with intensive collaboration among the design team members [9]. Otherwise, serious conflicts can arise (Figure 1) that effect both the load resisting and serviceability criteria of a building.

Counting purely on design codes is not sufficient as the code information and offered solutions only partly address the full range of concerns for timber buildings. Therefore, it is crucial to address taller multi-storey timber buildings from a collaborative and interdisciplinary perspective, considering static, dynamic, fire, acoustic, human health and other aspects in parallel and not in isolation. Only through interdisciplinary analysis and interaction can a set of holistic design guidelines be developed that will enable safe construction of taller timber buildings that respect human well-being demands.

The main objective of HELEN is to foster international interest and effort in developing a shared understanding and deriving common guidelines for the holistic design of taller timber buildings. This will be carried out through the sharing of technical and scientific skills from the different and diverse research profiles within the network as well as their research facilities. Cooperation within this network will allow for coordinated research efforts and achievement of the following objectives:

- Coordinate, compare and bring together results of related research with the aim of defining optimized holistic approaches to improve the performance of taller timber buildings.
- Collect case studies that show flagship examples describing taller timber building design.
- Foster the transfer of knowledge among different actors in order to find suitable applications in various multidisciplinary fields (e.g. vibrations of buildings, material response and influence).
- Serve as a hub to combine existing knowledge and identify common issues and problems in order to develop new holistic taller timber building design guidelines.
- Suggest new design approaches, processes and technologies that can build and improve upon existing best practices and finally presented in the design guidelines suggesting the optimal holistic design of taller timber buildings.
- Identify and address regulatory, governance, financial and legal drivers and barriers for a wider implementation and use of taller timber buildings.

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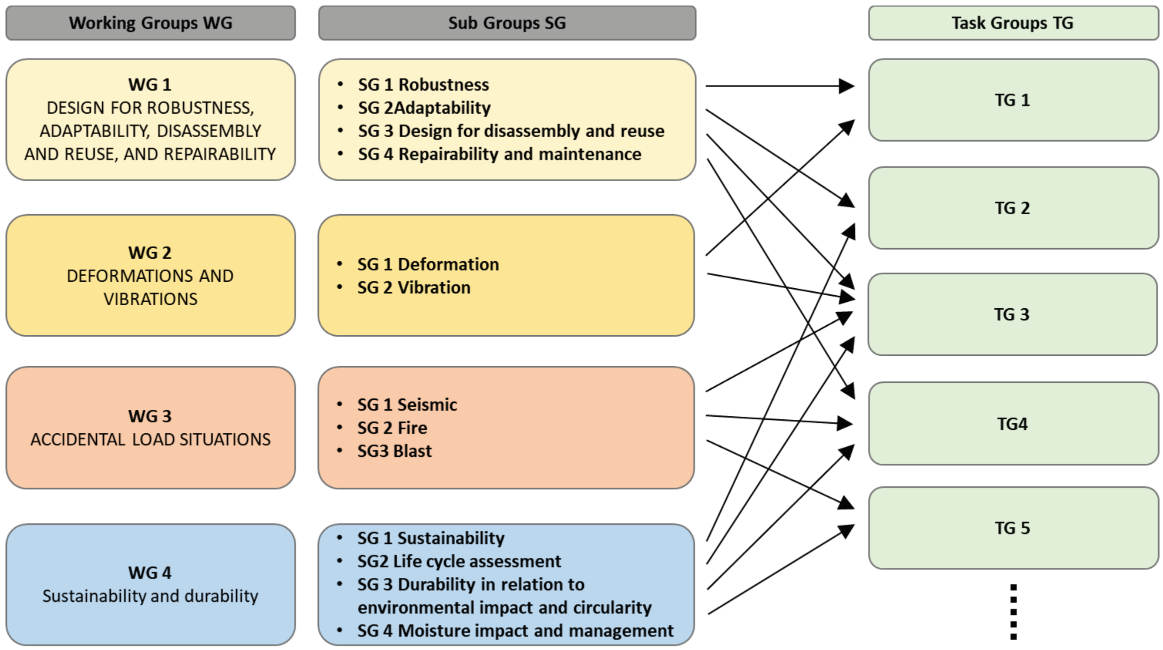


***Figure 2**: Structure of COST Action CA* 20139

## 3 STATE-OF-THE-ART REPORT

HELEN is organised in four Working Groups (WGs), each containing several subgroups (SGs). An overview is presented in Figure 2. As a result of the multidisciplinary aspects considered in HELEN, the COST Action is rapidly growing with currently 282 members from 44 countries (status March 2023).

One of the first targets on HELEN was the development of a state-of-the-art report in taller multi-storey timber building design fields: 1) Design for robustness, adaptability, and reuse and repair; 2) Deformations and vibrations; 3) Accidental load situations and 4) Sustainability and durability. In this chapter, the WGs and the content of the State-of-the-Art report is shortly introduced.

One of the main activities of the action is the identification of multidisciplinary tasks and research questions, for which the expertise of several WGs can be combined in task groups (TG) in a multidisciplinary effort (Figure 2). The State-of-the-Art Report was a first step in the identification of such multidisciplinary issues.

### 3.1 WG 1 – DESIGN FOR ROBUSTNESS, ADAPTABILITY, DISASSEMBLY AND REUSE, AND REPAIRABILITY

WG1 deals with aspects related to *robustness, adaptability, design for disassembly and reuse, and repairability*. Given the broad range and interdisciplinary nature of the topics assigned to WG 1, it has members with different backgrounds in both engineering and architecture and in research and practice. WG 1 is organised in four Sub-Groups (Figure 2) i) SG *Robustness*; ii) SG *Adaptability*; iii) SG *Design for disassembly and reuse (DfDR)*; and iv) SG *Repairability and maintenance*. The contribution of WG 1 to the State-of-the-Art Report [10] includes a total of 20 documents from all SGs.

<u>*Robustness:*</u>
SG *Robustness* deals with the topics of resistance to disproportionate damages, including structural and non-structural robustness and resistance to progressive collapse. The SG has worked on developing a framework for the design of timber buildings against disproportionate collapse, which includes identifying all stakeholders and their interests and responsibilities. Case studies of structural design for increased robustness have been analysed and most important strategies summarised. The key issues identified by the SG are the: experimental validation of sudden element-removal scenarios; simplified structural analysis models for alternative load-paths (ALPs), e.g. with dynamic amplification factors; the behaviour of connections in ALPs; connections as fuse elements in segmentation strategies, which has similarities with *capacity design* for earthquake resistance; "power storeys" for vertical segmentation in taller timber buildings. The members of SG *Robustness* contributed with five documents to the State-of-the-Art Report.


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*Adaptability:*

SG *Adaptability* deals with topics related to changes in the functional use of buildings, how the design of tall timber buildings can account for adaptability-related requirements (e.g. versatility, convertibility, expandability), and with the interactions between these and other requirements (e.g. robustness, durability). The SG created a definition of adaptability of a taller timber building an identified key challenges and advantages of timber buildings. The SG is currently focusing on: identifying spatial structures and constructions that allow for the highest degree of interaction, flexibility and adaptability; identifying key parameters for adaptability; identifying conflicts between adaptability and other requirements (e.g. acoustics, fire safety); socioeconomic factors for higher adaptability; digitalisation, information management and computational methods for adaptability, repairability and reusability of timber buildings; development of reversible connection systems.

*Design for disassembly and reuse:*

SG *Design for disassembly and reuse (DfDR)* addresses the topics of design for disassembly and reusability in the context of tall timber buildings. This includes the design of new timber buildings taking into account future needs of disassembly and maximising reuse possibilities, but also the reuse of reclaimed materials in new buildings. The SG has been working on: identification of circular materials flows in tall timber buildings; assessment of the mechanical properties of reclaimed timber members; and identification of barriers to the design for disassembly and reuse.

*Repairability and maintenance:*

SG *Repairability and maintenance* deals with issues of maintenance of buildings during their planned service life and of restoring the original conditions in case of damages. The work of this SG has focused on: maintenance strategies for tall timber buildings; design strategies to take into account eventual need for repairs; repair strategies for tall timber buildings; and how to extend the service life of taller timber buildings.

### 3.2 WG 2 – DEFORMATIONS AND VIBRATIONS

WG2 deals with aspects and design issues related to *deformations and vibrations* in the framework of taller timber structures. Basically, scientist and professional engineers contributing to the activities of WG2 are representative of research institutions, universities and industrial partners. Actually, major activities of WG2 are divided into two major Sub-Groups: SG1 – Deformations and SG2 – Vibrations, see [11] and Figure 2. Besides, many tasks and sub-topics represent a critical input and vital part of discussion and elaboration in SG1 and SG2.

*Deformations:*

Talking about *deformations* in tall timber structures, the attention goes to a multitude of aspects and issues that have major effects in research and industrial applications and are often fairly addressed by existing standards and regulations. As a matter of fact, deformations in timber structures are primarily associated to joints and connections. There are however no doubts about the complexity and variability of possible technological solutions in the field of *joints* and *connections* for timber structures. Also, the type of load, the boundary conditions and the assessment of their mechanical performance suggests the need of a robust background in support of optimal and safe mechanical design of these systems.

*Vibrations:*

The issue of *vibrations*, which is also addressed by WG2 members, is implicitly related to deformations and corresponding gaps in engineering knowledge / design tasks. Starting from the assumption that *vibrations* itself is a rather general definition and can cover a multitude of practical / technical aspects in the framework of timber structures, WG2 members actively contributed to the elaboration of a State-of-the-Art document in which most of engineering terms and problems could be first defined in their context. So far, do we implicitly talk about vibrations in floors or partition walls for timber structures? And which kind of design action should be primarily addressed in terms of vibration serviceability, for the specific solutions in use in tall timber structures? But indeed, how can we monitor and control, or possibly minimize and mitigate the effect of vibrations in typical load-bearing components for tall timber structures?

The first elaboration from WG2 members, in this sense, resulted in the detection of rather wide and complex tasks in which – under the assumption of a joint primary goal of design – basic engineering knowledge for vibration assessment and mitigation is still represented by the need of standardized operational procedures and guidelines which could be efficiently applied to any type of building component (floors for instance, but not only). This need implicitly recalls the complexity of possible design actions (WG3 topic) and their effect and assessment in terms of vibrations. Human-induced loads on timber floors, for example, are totally different in dynamic and mechanical features (and effects) from wind pressure or seismic actions (and corresponding vibrations).

There are no doubts, finally, about the inter-correlation of *vibrations* and *deformations*, which again suggest an intrinsic mutual interaction of load-bearing components for tall timber structures and the final user / the design actions.

### 3.3 WG 3 – ACCIDENTAL LOAD SITUATIONS

The activities conducted in the first year on accidental load situations have been summarized in the form of a State-of-the-Art report [12]. The State-of-the-Art, developed with the contribution of 45 people from 17 different countries, aims to reflect the current knowledge on the development, design, and construction of taller timber buildings subjected to accidental load situations due to earthquakes, fires, and blasts. Particular attention was paid to the efforts and the proposals made to overcome the limitations for the progress in the

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construction market of mid-rise and taller timber building. The report is the result of a deep review of scientific literature, international collaborations, national regulations, design guidelines, as well as case studies. Potential interactions with other fields of design and to the efforts made in the recent years to overcome the limitations for the progress in the construction market of timber buildings were investigated. The indications collected represent the starting point of discussion to identify solutions, research targets, methods, and resources for the future of taller timber buildings under seismic, fire, and blast loads following a holistic design approach. Three different sub-groups (SGs) have been defined for WG3 State-of-the-Art activities, namely SG1 - Seismic Loads, SG2 - Fire and SG3 - Blast. For each SG, different subtopics have been analysed and discussed.

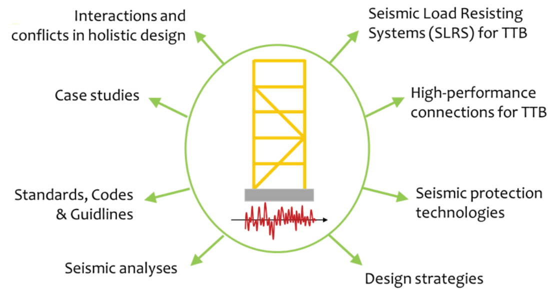


***Figure 3:*** *topics analysed by SG1 for seismic load on taller timber buildings.*

<u>Seismic:</u>

With potentially devastating effects on occupant safety and economic stability, earthquakes represent one the main hazard to consider when designing buildings in seismic prone areas. Despite possessing properties that make them well-suited for seismic design (i.e. lightness), timber structures are not immune to the effects of earthquakes. In light of the current timber construction sector growth, investigating the effects of earthquakes on taller timber structures is crucial to ensure life safety and minimal economic losses.

The primary focus of SG1 was to analyse how seismic activities impact tall timber buildings. In particular, eight topics were identified (Figure 3) and deeply examined, including: Lateral Load Resisting Systems (LLRSs), high performance connections, seismic protection technologies, seismic design strategies and analyses, standards and codes, analysis of case studies, and interaction and conflict in holistic design.

The State-of-the-Art report reveals that different LLRSs including shear walls, heavy frames and hybrid structural systems are typically adopted for taller timber buildings. Regardless of the structural system considered, connections are crucial for the seismic performance of timber buildings, as they determine their stiffness, capacity, and ductility. Two categories of connections were identified, namely traditional and innovative, and the need of connections with significant resistance and ductility was pointed out. Seismic protection technologies such as supplementary damping systems [13] and passive control systems can be used as viable solutions to reduce structural and non-structural damages and related economic losses, especially in areas with high seismic hazard.

The analysis of the design strategies and the seismic analyses indicates that capacity-design principles should be employed to ensure energy dissipation and optimal structural performance. Also, modern performance-based design, both force-based [14] and displacement-based [15], can be adopted to reach specific target performance. However, to date only a limited number of international codes has specific design guidelines for timber buildings subjected to seismic load. Further research is required in the near future to address seismic design-related issues, such as the in-plane behaviour of floor diaphragms, prediction of connection mechanical properties, and the interaction of structural elements. Finally, the analysis of case studies and discussions with designers emphasized the need for integrated design methodologies that optimize functions, minimize costs and errors, and avoid conflicts between different design strategies.

<u>Fire:</u>

Structural timber is often cited for its carbon storage and subsequently for offering a possible response to the current climate crisis. For fire safety implementation in buildings, it is, however, important to note that the presence of more potential fuel is a consequence of this carbon storage. The State-of-the-Art report indicates that the contribution of structural timber as a fuel to the fire can, among other things, increase the fire growth [16], the structural damage, and the external exposure of fires [17]. However, only a handful of countries to date have adopted provisions aimed at limiting the fuel contribution for the whole duration of the expected fire scenarios, such as by limiting the exposed surfaces of mass timber [18] and preventing glue line integrity failure [19], or accounting for its impact (e.g. by having construction type specific fire resistance requirements [20]). Although most previous research focussed on the performance of timber in standard fire resistance tests, knowledge gaps regarding connections, multi-span structures, point loaded panels, and connections [21] relevant for taller timber buildings were identified. These gaps are especially pertinent when considered for the combined action of earthquakes or blasts and fires. The State-of-the-Art report also indicated that only a small amount of data was found relevant for robustness, post-fire repair, fire suppression strategies, which are topics mainly related to the protection of property.

<u>Blast:</u>

The increase in market share of the timber construction industry brings with it an increase in potential exposure to accidental and intentional blast explosions, such as that emanating from gas leaks and vehicle bombs, respectively. Understanding how wood behaves under high strain-rates and having well-established mitigation


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strategies to minimize the risk of progressive collapse is required to ensure occupant safety during these rare events. As an organic material, high strain rate effects and failure modes were found to be affected by the direction and rate of the load in both members [21-23] and connections [24-25]. With that being said, present-day blast design codes were developed based on preliminary data which are no longer applicable to the novel engineered wood products. As in the case of connections for seismic detailing, connections of timber assemblies under blast load must be designed to concentrate the majority of the deformations within ductile connectors, to protect the load-bearing timber element against unwanted damage [e.g. 26- 27].

Particular attention should be given to the brittle behaviour of timber in order to minimize the risk associated with progressive collapse in timber structures. Another consideration was ensuring that connections and main elements had sufficient ductility and strength in addition to ties consideration in the main principal directions [28]. While simplified modelling methodologies were praised for their proven efficacy and low computational costs [29], they lack the ability to consider and capture multiple failure modes. This may be circumvented using finite element modelling (FEM); however, proper attention is required to develop a representative material model that can treat wood and its many failure modes, including both brittle and ductile failure modes.

### 3.4 WG 4 – Sustainability and durability

A holistic design approach can make taller timber buildings even more sustainable compared to conventional buildings made mainly of steel, concrete, or masonry. Durability is meant in terms of moisture safety for longevity of timber products, assemblies and structures, and the possibility to increase utility by e.g., reuse or quality cascading in upcoming product life. Robustness should express the general resistance of timber against moisture within certain limits. To not exceed these limits, a proper moisture management is necessary and must be considered already in the holistic design for taller timber structures, considering the different stages from factory until operation. Robustness also has to do with the resilience of structures and assemblies and their repairability to maintain most of the moisture affected situations. This robustness concept exercised for entire buildings also enables to additionally lower environmental footprint because it allows to keep buildings in service as long as technically possible. Therefore, many crosslinks with Working group 1 - Robustness, Reuse and Repair of CA20139 exists.

To benefit from these advantages, tall timber buildings must have a similar or almost equal durability compared to conventional buildings. Otherwise, the sustainability advantages would be compromised. Therefore, tall timber buildings must be designed, considering the special properties of timber as construction material. The goal is to maximize resistance of this type of timber structures and envelope systems against various moisture exposure scenarios causing deterioration and damage. Not only design but also execution of timber structures is of relevance namely construction site activities and prevention from severe moisture impact. Further operation and maintenance of large and tall timber buildings need a focus on risk reduction measures.

Despite these special requests for the designers, tall timber structures are already built in Europe, but also North America and Australia are competing since a few years. Thus, a lot of research work and development have been done especially in Europe on this field.

The aim of Working Group 4 is to report the state of the art in terms of research and practice of durability and sustainability of tall timber building systems, in order to summarize the existing knowledge in the single countries and to develop a common understanding of the design for moisture safe and robust execution and operation of tall timber buildings. The State-of-the-art report reflects parts of the work and the discussions within WG 4 [30] and covers the SG topics given Figure 2. It intends to give information and studies available around the world, but especially in Europe through the active contribution and participation of experts from various countries involved in this Action.

Exchanges of experts are planned in order to achieve a harmonisation of concepts, approaches and methods, e.g. in the field of life cycle assessment for taller timber buildings. Gaps in knowledge over all four parts of WG 4 (Figure 2) will be defined and built up the framework for further research projects and collaborations. Existing expertise’s are to be presented and passed on to a wider range, of timber engineers and practitioners within training schools, online seminars or specific short term scientific missions educating especially the younger generation, the engineers of our future.

## 4 SHORT-TERM SCIENTIFIC MISSIONS

Short Term Scientific Missions (STSM) are aimed at supporting individual mobility and at strengthening the existing networks and fostering collaborations by allowing scientists to visit an institution or laboratory in another Participating COST Country or an approved institution. A STSM should specifically contribute to the scientific objectives of the COST Action, while at the same time allowing applicants to learn new techniques or gain access to specific instruments and/or methods not available in their institutions. In doing so, the COST Action addresses with the STSMs in particular the needs of young scientists to build and strengthen their network and supports diversity in the field. In the first Grant period of HELEN (the year 2022), six STSMs were conducted, covering the following topics:

- Experimental and numerical assessment of soundproofing interlayers influence on the

strength and stiffness of timber to steel screw connections
- Fire induced delamination
- Influence of elevated temperature on the adhesive used in hollow glue-laminated timber elements
- State-of-the-art report on realistic fire exposure in fire design of taller timber buildings
- Towards Zero Carbon Buildings: Timber structure for sustainable buildings
- Environmental impact assessment of multi-storey residential timber buildings – integrated approach

The COST Action is committed to promoting the development of novel applications and will consistently allocate additional resources towards new research initiatives.

## 5 COMMUNICATION

The HELEN COST Action has generated interest from a broad range of stakeholders, who are involved in the WGs, such as representatives of the timber construction industry, architects, structural engineers, consultants, builders, product developers in the sector of timber structures, authorities and policy makers at regional and European levels, research community, relevant standardization bodies and code writers, teachers, lecturers and students of structural design, engineering, and architectural schools.

The COST Action aims at connecting these stakeholders and communicate its activities to the stakeholders, research community, and society, amongst others by:

- Sharing research results
- Stimulating new research projects
- Raising awareness of the Action topics in general public and among scientific societies
- Engaging the stakeholders
- Influencing policy making
- Exchanging ideas on sustainable development of the built environment

The discussion of the research efforts and the development of the research results are realized through workshops, seminars, and STSMs. The consolidated results of the action are disseminated and communicated through conferences, training schools, and the joint elaboration of state-of-the-art papers, best practice examples and final design guidelines for a holistic design and construction of taller timber buildings.

The workshops, conferences, and training schools to be carried out within this Action promote the interdisciplinary research in the fields of wood science and technology, timber engineering and structural reliability. The first training school in 2023 covers the holistic design of connections in timber structures and all WGs are involved in its preparation. Further training schools on interdisciplinary topics are planned for the following years.

## 6 CONCLUSIONS

The very essence and key to a successful COST Action will be intense interdisciplinary work with in-depth discussions and debate over a series of hypothetical and real case studies, followed by focused research work. Contrary to common building research work done in the past, where individual topics were assessed in depth by specialised teams working on isolated topics (i.e. just timber connections or just vibration of floor plates), research within HELEN will be intensely collaborative and integrated.

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