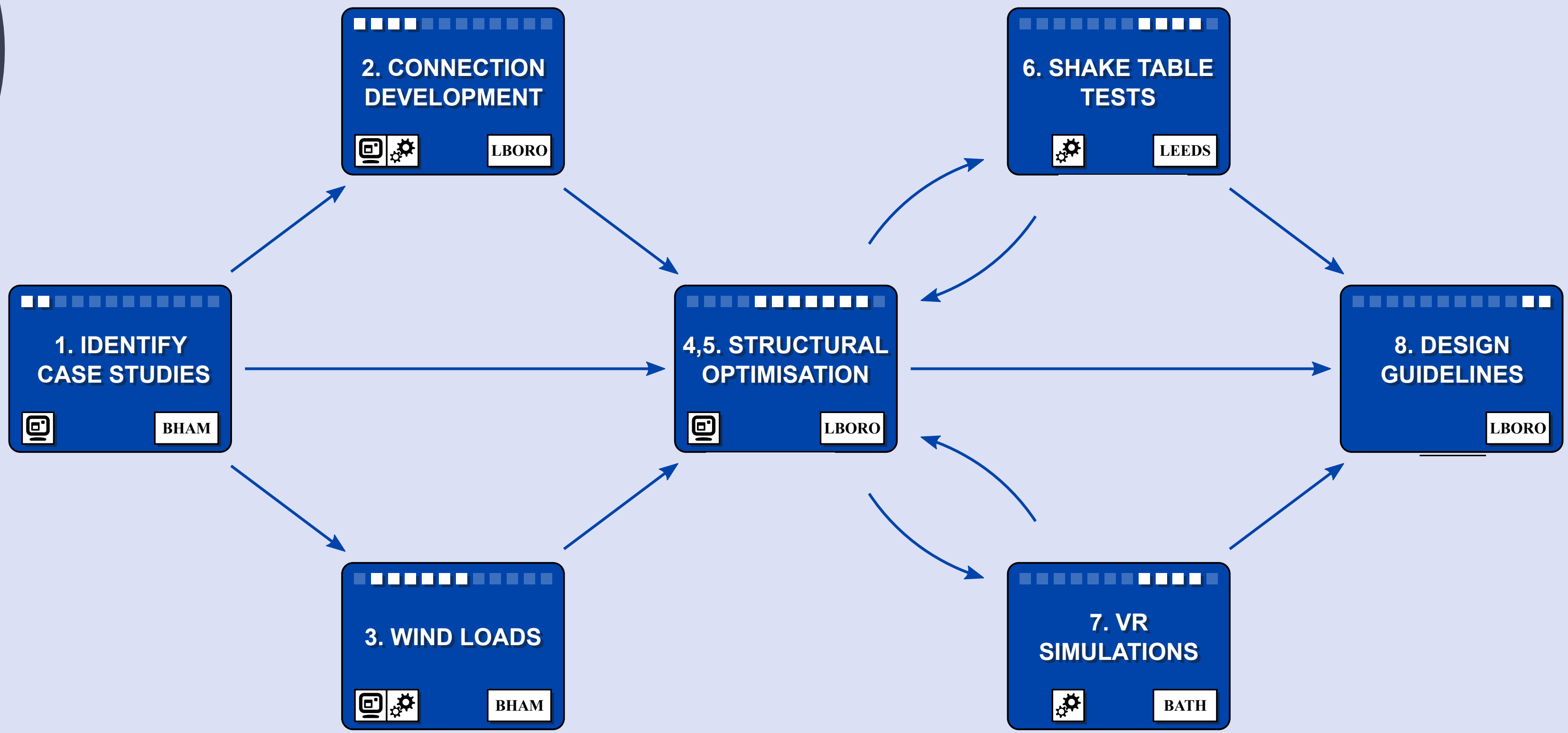
“Optimal Multi-Hazard Resilient Design of Tall Buildings with Double-Skin Façade”

Project’s Mind Map

OPTIMAL MULTI-HAZARD RESILIENT DESIGN OF TALL BUILDINGS WITH DOUBLE-SKIN FAÇADES

- LBORO Loughborough University
- BHAM University of Birmingham
- LEEDS University of Leeds
- BATH University of Bath



WP#1. Definition of the case-study prototype buildings

Led by Bham's Marios Theofanous | Months 1 to 6

- **Nine design situations** will be considered, across **three different cities** (possibly, London, Lisbon and Istanbul, representing locations with "negligible", "moderate" and "high" seismicity) and **three building heights** (maybe, 20, 40 and 60 storeys, covering 99% of tall buildings in the 2018 London's pipeline by number of storeys).
- Structural materials and type of lateral force resisting systems for the prototype buildings will be selected in **dialogue with engineering consultants and contractors** previously involved in the structural design and construction of major skyscrapers built or under development in Europe and around the world, so to be **fully representative of the current best practice**.
- **Irregularities in plan and in elevation** will be introduced in the prototype models, so to accommodate **illustrative aesthetic and functionality requirements**, as advised by **architectural designers**.

→ *This comprehensive set of design scenarios will be used in subsequent WPs (work packages) to robustly assess the effectiveness of the proposed structural control solution.*

WP#2. Dynamic characterisation and design development of DSF links

Led by Lboro's Alessandro Palmeri| Months 1 to 12

- Static and cyclic tests will be performed at Lboro's Civil Engineering **Structures and Materials Lab**, in order to fully capture **stiffness, damping and fatigue behaviour** of commercially available connectors, selected **in agreement with façade consultants and industrial manufacturers**.
- Based on the outcomes of the experimental campaign, modifications will be proposed and implemented to **improve the overall performance of the links**.
- **Numerical models** of these connectors will be developed and validated against the experimental results. These models will allow performing initial **dynamic analyses**, exploring feasible ranges for the links' mechanical properties that ensure maintaining sufficient strength and stiffness under the design actions while simultaneously providing adequate damping and degree of movement for the DSF elements to act as vibration absorbers.

→ *The effects of different forms of energy dissipation will be quantified, thus partially shaping the search space and constraints for the structural optimisation carried out in WP#5.*

WP#3. Numerical and experimental aerodynamics of buildings with DSF

Led by Bham's Hassan Hemida | Months 4 to 21

- Computational fluid dynamics (**CFD**) and **physical testing** will be used to better understand how **extreme wind conditions** affect high-rise building with DSF.
- **In consultation with the industrial partners**, **different types of DSF** will be studied, e.g. "continuous", "corridor" and "box", which differ on how the ventilation air flow is constrained.
- Regular and irregular 20-storey building models, 1:150 scale, equipped with different types of DSF, will be mounted in the Bham's **Environmental Wind Tunnel**. The pressure coefficients on both the outer and inner surfaces of the DSF will be statistically quantified for different angles of attack of the wind.
- The same models will be tested in the Bham's **Tornado Simulator**, varying distance from the centre of the tornado and orientation with respect to the radial velocity.
- CFD analyses based on the Detached Eddy Simulation (**DES**) will be carried out, representative of windstorms and a tornado-like flows. These simulations will provide detailed description of the aerodynamic forces and flow field around the building in both time averaged and instantaneous frame of work.

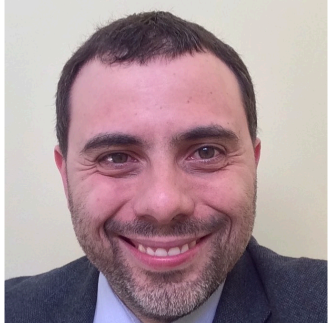
→ *The results collected as part of this WP will directly inform the multi-hazard optimisation in WP#5, providing the accurate definition of the dynamic actions for the windstorm and tornado scenarios, also weighing the uncertainty associated with global worming and climate change*

WP#4. Definition of a rigorous multi-hazard resilience-based engineering framework

Led by Lboro’s Alessandro Palmeri | Months 13 to 18

- Starting from the **probabilistic characterisation of the intensity measures** (IMs) associated with earthquake and wind actions (namely, **spectral pseudo-acceleration** and **mean speed**), a rigorous approach will be developed to quantify the building’s **life-cycle cost** (LCC). This key performance indicator will include direct and indirect costs due to structural and non-structural damage and restoration, and those due to the building’s downtime and loss of functionality caused by lack of comfort.
- To enhance the framework’s robustness, both dynamic actions and fragility functions will be represented through **imprecise probability** models, where the statistical descriptors of a suitable probabilistic distribution, e.g. mean and standard deviations, are treated as bounded fuzzy variables.
- The availability of this **rigorous framework** will support the decision makers to holistically compare different design solutions.

→ *The optimisation in WP#5 will be performed within the devised framework.*



WP#5. Multi-criteria structural optimization

Led by Lboro's Giorgio Barone | Months 16 to 33

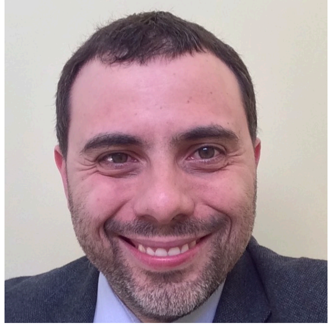
- A multi-hazard, multi-objective optimisation procedure will be established in order to identify **optimal design solutions** for tall buildings equipped with DSF.

- *For each representative case study identified in WP#1:*
  - *i. the structural topology of the main building structure will be considered as a design constraint;*
  - *ii. the structural elements of both main building and DSF will be optimised by minimising the initial construction cost (ICC) under static gravitational and lateral loads, to provide a reference design configuration;*
  - *iii. for each chosen location, the combination of main building and DSF will be optimised under seismic and wind actions, as characterised in WP#3 and WP#4.*

- *In this stage of the process, the **design variables** (DVs) will include:*
  - *stiffness, strength and ductility of the lateral-resisting elements;*
  - *topology, stiffness, strength and damping of the DSF, including the connectors analysed in WP#2.*

- **Meta-heuristic methods** will be adopted to perform the multi-objective optimisation. Both ICC and LCC will be minimised under **multi-faceted nonlinear constraints** (e.g. availability of certain components in the market, aesthetics and energy efficiency of the design, etcetera). The overall computational burden will be reduced using **surrogate models**.

→ *This WP will deliver a robust tool for identifying, in a probabilistic sense, sets of optimal design solutions (known as **"Pareto optimal front"**) and could then be adapted to a broad range of design problems in which prioritising ICC vs LCC could lead to very different solutions.*



WP#6. Dynamic testing of DSF-controlled frames

Led by Leeds' Nikolaos Nikitas| Months 22 to 33

- The effectiveness of DSFs as vibration absorbers will be demonstrated through a series of **shake-table tests** carried out on **scaled 3-dimensional models** using **Leeds's new EPSRC-funded facilities**. The reduced models will be dynamically similar to selected case-study buildings identified in WP#1, with optimal DSF configuration identified in WP#5.
- Tests will **validate the computational models** developed in WP#5 and assess the potential effects of **combined nonlinearities** in both the primary structure (eg ductile behaviour) and DSF (eg mechanisms of energy dissipation in the connections).
- **White noise table shaking** of increasing intensity will be applied for establishing damping evolution for critical vibration modes in uncontrolled and controlled configurations. The dynamic performance of the system will also be assessed during **realistic earthquake shakings** of increasing intensity, establishing damage location and extent after each test.

→ *The experimental campaign will demonstrate the performance of the DSF under high-intensity seismic events, allowing for updating the numerical model established in WP#5 and informing the development of the design guidelines in WP#8.*

WP#7. Virtual-reality tests

Led by Bath's Antony Darby| Months 22 to 33

- The effects of vibrating DSFs on the **comfort of building occupants** will be investigated using Bath's new EPSRC-funded VSimulator sway motion platform and virtual reality (VR) facility.
- **Visual cues** influence the perception of movement, such that the contrast between sway of the structure as a whole and the exaggerated motion of the DSF as it dissipates energy may be counterproductive to **occupiers' comfort and anxiety**. Bath's facility will therefore simulate the motion of a tall building with and without DSF, allowing a rigorous assessment of how the simultaneous motion of the building structure and its outer skin affects the perception of movement and hence influences their comfort and well-being.
  - 3-D CAVE-type VR will be used to simulate the façade configurations and the resulting different levels of its movement, while physical movement of the building is provided by the motion platform. Both virtual and physical motion will be simulated according to the numerical model devised in WP#5.
  - Subjects will be tested in the VSimulator's CAVE using rigorous psychological protocols, with appropriate measurements used to assess their level of stress.

→ *This experimental campaign is particularly significant to assess the performance of the DSF under wind actions of increasing intensity, informing the development of the design guidelines in WP#8.*

WP#8. Development of design guidelines

Led by Lboro's Alessandro Palmeri | Months 31 to 36

- All relevant results derived from the previous WPs (work packages) will be assimilated, integrated and synthesised to form a set of **comprehensive design guidelines** that can support structural engineers working on the design of tall buildings, as well as researchers and practitioners interested in innovative strategies to control seismic- and wind-induced structural vibrations.
- To maximise dissemination of the research findings outside academia, a **"white book"** will be published, with inputs from all the academic and **industrial partners** involved in the project, and the document will be presented as part of a one-day workshop organised in London under the auspices of the Institution of Structural Engineering, IStructE (and maybe the Society of Façade Engineering, SFE, too).
- Other **stakeholder-specific training sessions** (e.g. tailored CPD courses) could be also organised to benefit the project partners.