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Simulation of Complex Brain Surgery with a Personalized Brain Model

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A common cause requiring invasive brain surgery is fatal pressure from swelling-induced deformation. Neurosurgeons try to relieve pressure using decompressive craniectomies, which involves cutting into the skull to allow the brain to 'bulge out'. Even though this surgery has been happening for over a century, surgeons have little else other than previous experiences to help reduce the risk of post-surgical complications such as severe disabilities; even slight changes in mechanical conditions can have devastating results on the brain. During decompressive craniectomies, nerve fibres in the brain, known as axons, stretch, and run the risk of shearing, making this procedure a 'last resort' for surgeons. Precise criteria are unavailable to surgeons for determining factors such as timing, as well as the optimal location and size of the skull opening.

New solutions developed by researchers at Stevens Institute of Technology, Stanford University, Oxford University, and University of Exeter tackle this problem through a Finite Element (FE) model of the brain created in Synopsys Simpleware software [1, 2]. The model is used to simulate craniectomy procedures under different conditions. The use of these methods gives neurosurgeons insight into extreme tissue kinematics, enabling them to plan the shape and position of the craniectomy.

Building a Brain Model

The brain has 86 billion neurons and 10 trillion synapses, meaning that it is very complex and hard to model, with many variations between different regions. By splitting the brain and skull into different geometric structures using FE modelling, it is possible to break down this complexity and gain insights into their mechanical response. Simulation of the brain enables understanding of different regions and how they are affected by environmental factors and pathologies, enabling prediction of the deformation field, dimensions of bulging tissue, strain field, and regions at risk for local tissue damage.

To capture this level of detail, researchers used MRI data to create a model of the brain for pre-surgical planning. The image set contains 190 slices in the sagittal plane taken at a spacing of 0.9mm. Each image slice has a matrix representation of 256 × 256 pixels with an in-plane resolution of 0.9mm × 0.9mm. Images were acquired using a 3 Tesla (3T) scanner with a 32-channel radiofrequency receive head coil. The images shown in Figure 1 were acquired from a female adult's head at the Stanford University Centre for Cognitive and Neurobiological Imaging using a 3T scanner. The image data was then imported to Synopsys Simpleware software and processed to create a geometrically faithful 3D model. 190 2D slices of the brain were combined to create the 3D model. The researchers quickly visualized and identified relevant regions of interest within the brain, for example, differences between white and grey matter within the MRI were used to identify tissue. Other features such as cerebrospinal fluid, the cerebellum, skin, and skull could also be identified using this technique. Capturing the fine details of the skull and brain is crucial to being able to rely on the 3D model as a surgical reference.

One challenge of working with image data involves converting segmented images into a usable FE mesh for simulation. Often, those working with this type of data use multiple software packages and have to 'fix' broken meshes, reducing the model fidelity. [3].

After segmenting regions of interest from MRI scans, voxels are extracted and a surface or volume mesh is generated. The advantage of having an image-based FE model is that it can better capture the complexity of the brain and related anatomical regions, increasing the quality of the simulation. Non image-based FE models are often simplified representations of brain anatomy that are generated for specific simulations, and are not easily adaptable, nor are they realistic enough for other simulations.

The image-based FE mesh was highly detailed, and included tissues and features within the brain such as cortical fields. The top left image in Figure 2 shows the specific relative locations of these individual substructures and their dimensions within the skull. In addition, the six images at the top right of this figure can be used to visualise mesh contours and geometric outlines of cerebral and cerebellar white matter, the cerebral gray matter, and the skull. The images in the lower row of this figure show coronal sections throughout the entire brain model. The meshing algorithms used in the software ensured a numerical model that maintained fidelity to the original scans after processing, removing the need to re-mesh in a simulation solver and making it numerically reliable. By avoiding this typically time-consuming stage in a simulation workflow, researchers were able to quickly generate robust meshes for analysis. Colour mapping of the different regions of the model also made it easier to identify how individual parts of the anatomy interact (Figure 2).

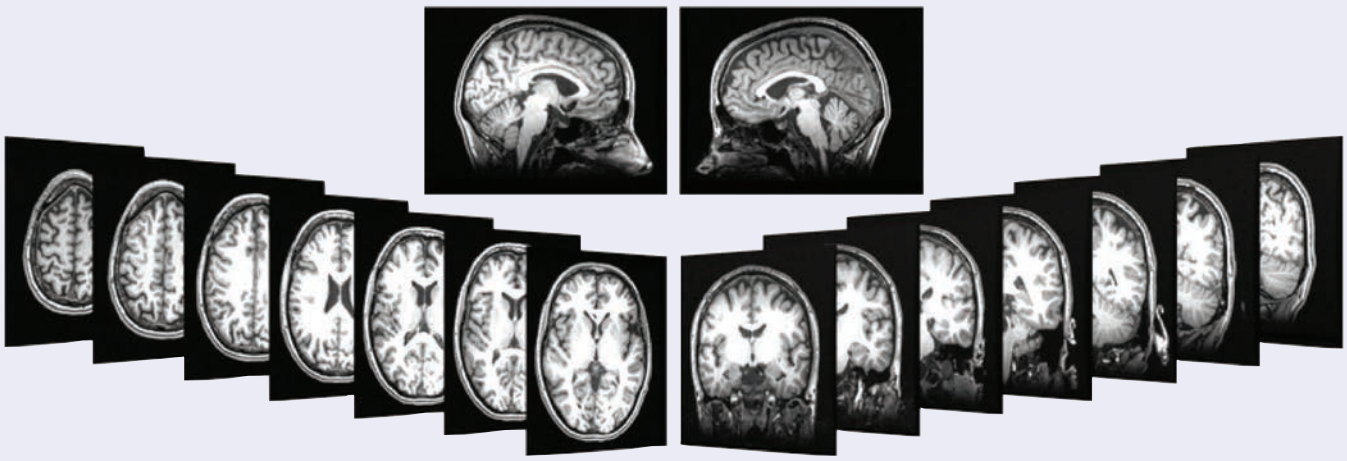

Figure 1: Magnetic resonance images of an adult female brain.

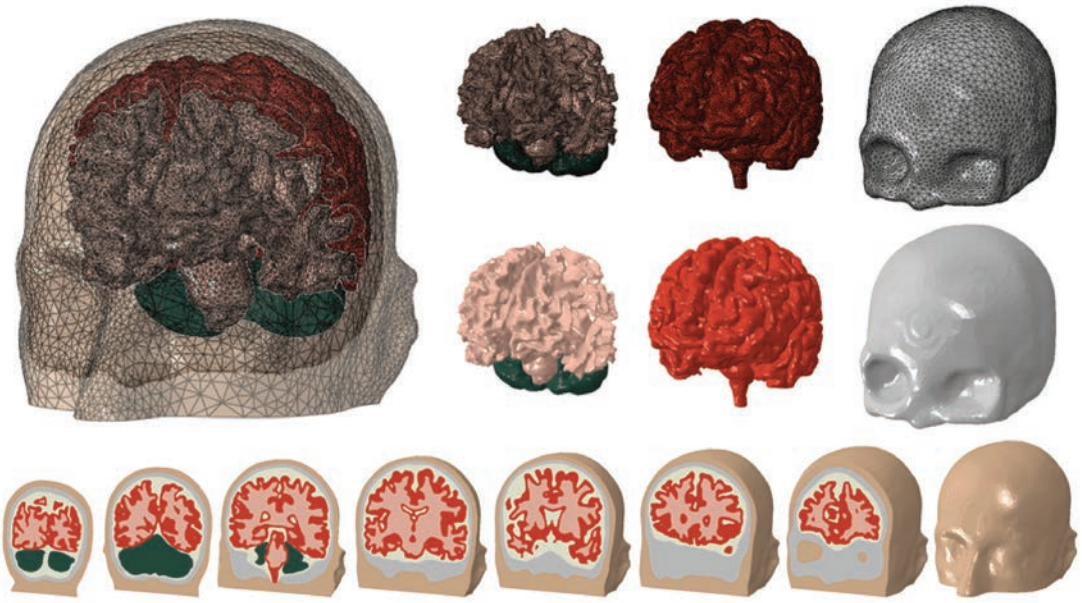

Figure 2: Personalized finite element model of the head including the skull (gray), the skin (brown), the cortical gray matter (red), the inner white matter (pink), the cerebellum (green), and the cerebrospinal fluid (beige).

Gaining Insights into the Brain Through FE Simulation

The simulation involved developing craniectomy models with two different skull openings: a frontal flap and a unilateral flap. The mesh was exported to SIMULIA Abaqus software where material models, boundary conditions, and interaction constraints for the individual substructures were defined. Virtual evaluations were carried out investigating different scenarios for swelling and the mechanical load on the brain from a decompressive craniectomy (Figure 3). These included a maximum volumetric expansion of 10% in the white matter tissue of both hemispheres, as well as exclusively in the collateral left hemisphere, and in the contralateral right hemisphere.

This approach considered the effect of the displacement field, maximal principle strain, and radial and tangential axon stretch. One of the key challenges of this simulation was to identify an optimal opening size to maximize control of pressure and minimize the risk of axonal damage. Analysis of results identified high stretch levels, including potential issues with herniation and the risk of shear at the edge of the skull opening. Researchers were able to predict that 10% tissue swelling leads to axon stretches of up to 30%, and that a larger skull opening reduces and distributes axonal loading in the brain (Figure 4). Other insights included that opening up the skull on the same side as the swelling produces better results for patients. Results were consistent with the decompressive craniectomy procedure usually performed by clinicians.

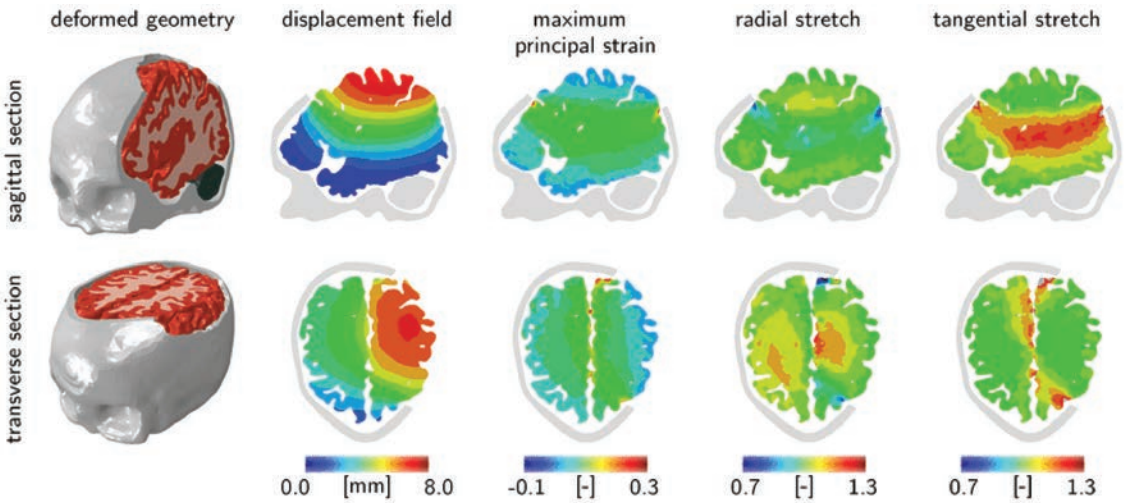

Figure 3: Sagittal and transverse sections of the computational simulation of decompressive craniectomy in response to swelling of the left hemisphere. Columns show the sagittal and transverse sections of the deformed geometry, displacement, maximum principal strain, radial stretch, and tangential stretch.

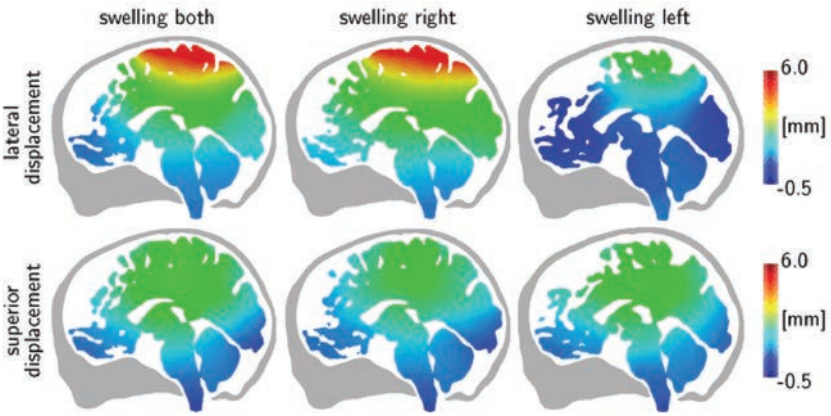

Figure 4: Midline shift for three different scenarios of brain swelling. Rows show the lateral and superior midline shift in sagittal sections. Columns illustrate a swelling of 10% in the white matter tissue of both hemispheres, exclusively in the right hemisphere, and exclusively in the left hemisphere.

Conclusions

The personalized head and brain model created for this project offers an effective tool for improving outcomes for highly invasive surgical procedures. FE simulation is valuable for locating pressure and damage zones on the brain, giving neurosurgeons large amounts of data to use in pre-clinical planning of procedures. In addition, the simulation of different scenarios makes it possible to tailor procedures to individual patient anatomies, and to cover a wide range of potential variables for a surgery.

Some of the potentially longer-term clinical impacts of this workflow include a lower risk of surgical complications, which are often fatal, and can be mitigated by extensive virtual evaluation before physical surgeries. The ethical considerations associated with decompressive craniectomy can also be evaluated by understanding different outcomes, and where failure can occur. Compared to experimental testing, for example rare in vivo measurements of strain, FE simulations can improve clarity and quantify strain fields without the need for invasive procedures.

Future studies of these surgical problems can be enhanced by adding additional structures and modelling dynamic strain rate effects, or porous effects that can affect the surgery. Use of a homogeneous brain microstructure, tissue, and cerebrospinal fluid also potentially obscures regional variations. Surgical risks such as infection, wound healing, and post-operative cranial reconstruction, are also important to understand for clinicians deciding on a patient's procedure.

Brain models based on 3D imaging data are also suitable for predicting extreme tissue kinematics and exploring the benefits of a larger skull opening without the need for high-risk surgeries. This type of detail has broader applications to any simulation involving brain injury or impact, as well as to evaluating procedures that involve electrical current being applied to the skull through medical devices. More complex modelling of the skull and brain is also valuable for looking at concussions and other types of damage.

The use of image based modelling to bridge MRI with engineering analysis packages promises to increase opportunities to improve surgical procedures and develop patient-specific therapies that reduce risk and shorten recovery time. Clinicians can rationalize decisions and go beyond intuition to arrive at a more optimal method for minimizing risks. FE models as inputs for surgical planning remain an exception rather than the rule, making the development of these more sophisticated models crucial to validating the method. ■

References

[1] Weickenmeier, J., Saez, P., Butler, C. A. M., Young, P. G., Goriely, A., & Kuhl, E. (2017). Bulging Brains. Journal of Elasticity, 129(1-2), 197-212. doi:10.1007/s10659-016-9606-1

[2] Weickenmeier, J., Butler, C. A. M., Young, P. G., Goriely, A., & Kuhl, E. (2017). The mechanics of decompressive craniectomy: Personalized simulations. Computer Methods in Applied Mechanics and Engineering, 314, 180-195. doi:10.1016/j.cma.2016.08.011

[3] Young, P.G., Beresford-West, T.B., Coward, S.R., Notarberardino, B., Walker, B. & Abdul-Aziz, A. (2008) An efficient approach to converting three-dimensional image-data into highly accurate computational models. Philosophical Transactions of the Royal Society A: Mathematical Physical Engineering Sciences. Vol 366 (1878) 3155-3173

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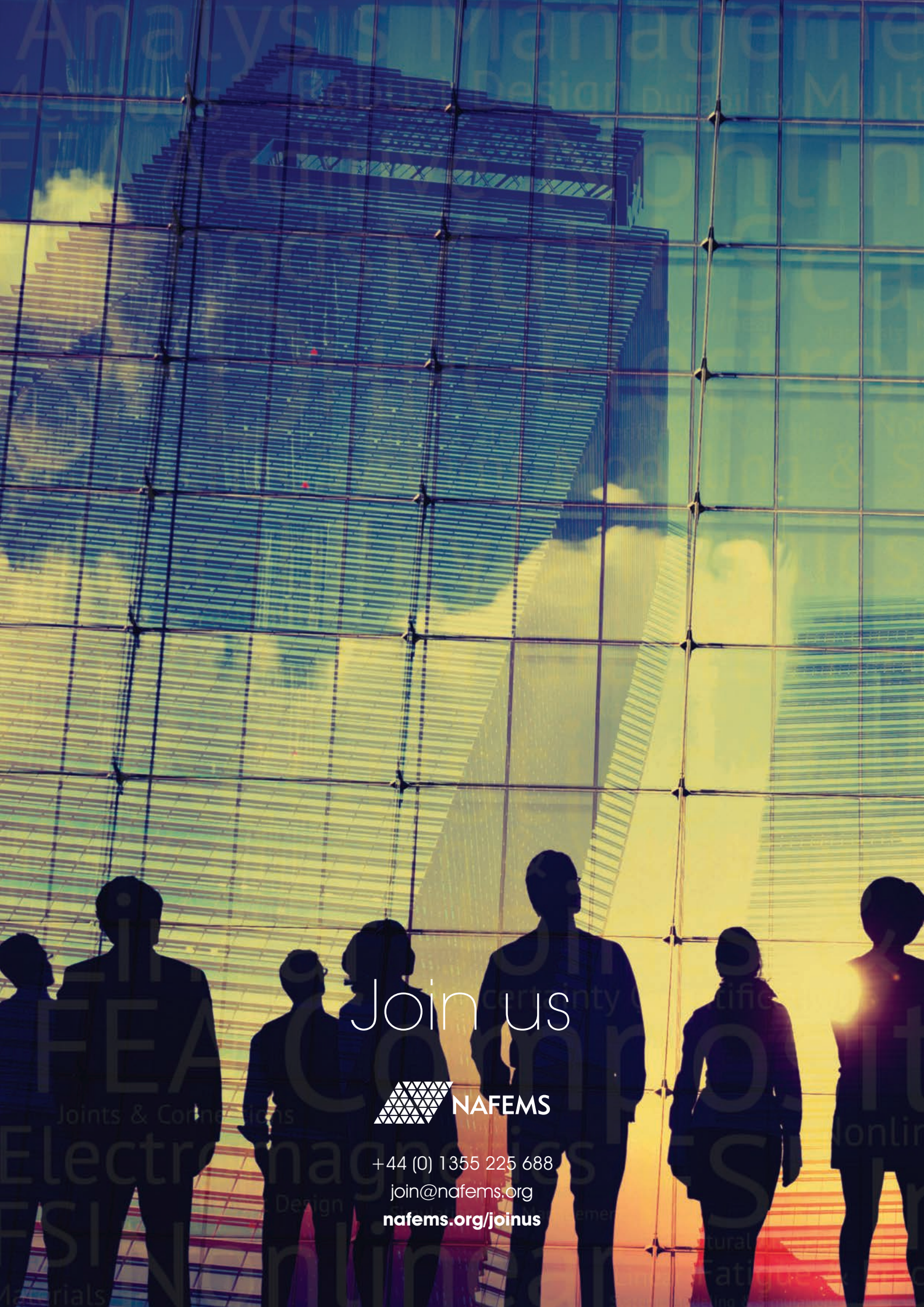
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