Converting finite element models to irreducible element models for use in population-based SHM

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Converting finite element models to irreducible element models for use in population-based SHM

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ABSTRACT: Population-Based Structural Health Monitoring (PBSHM) has emerged as a promising approach to increase the understanding of structural health by leveraging data from a population of structures, surpassing the insights attainable from individual structures alone. For successful knowledge transfer in PBSHM, structural similarities need to be established to prevent negative transfer effects. Irreducible Element (IE) models, combined with graph theory, are the vehicles used within PBSHM to facilitate this process. This paper presents a Finite Element (FE) to Irreducible Element model converter. While FE models are conventional in civil engineering, IE models represent a novel technology tailored for PBSHM, with limited available tools for their creation. This paper details a procedure for transforming FE models into IE counterparts. By enabling the conversion of existing FE models into IE models, this tool mitigates the need for specialised IE model expertise, resulting in more accessibility and ease of adoption of PBSHM. The significance of the FE to IE converter in the field of bridge Structural Health Monitoring is that it can help bridge the gap between conventional SHM and emerging PBSHM. The conversion tool also significantly enhances the accessibility of PBSHM in the civil infrastructure industry. The converter's utilisation holds the potential to accelerate the adoption of PBSHM by enabling the incorporation of an expansive array of structures with pre-existing FE models into the PBSHM framework.

1 INTRODUCTION AND APPLICABILITY OF FINITE ELEMENT (FE) MODELS

PBSHM leverages data from multiple structures within a similar population, providing an understanding and insights into the population and other similar structure (Worden et al., 2020). Populations of bridges can be wide ranging an example of a very similar population may be 2 or more steel truss pedestrian bridges however induvial elements can also be considered such as a population of bridges that all contain a ladder deck. Monitoring a population of structures, PBSHM offers a distinct advantage over traditional single-structure monitoring approaches which is the potential for transfer learning. Transfer learning is a method where knowledge gained from training a model on one task is leveraged to improve the performance on a different but related task. Instead of training a model from scratch for each new task, transfer learning allows pre-trained models to serve as a starting point, with the hope that the knowledge gained from one domain can be beneficial in learning another. However, the effective application of transfer learning between structures within PBSHM, which seeks to harness the knowledge gained from one structure to provide insights into others, hinges on establishing structural similarities that prevent negative transfer. To this

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end, Irreducible Element (IE) models, combined with graph theory, serve as a fundamental vehicle in PBSHM, facilitating the identification of structural commonalities and differences. More information about the foundations of PBSHM can be found in (Bull et al., 2021; Gardner et al., 2021; Gosliga et al., 2021; Tsialiamanis et al., 2021).

Concurrently, the field of civil/structural engineering has used Finite Element (FE) models as a fundamental numerical tool for analysing and simulating structural behaviour. FE models have a rich history of application, but as PBSHM is at the early stage of development, there is a growing need to bridge the gap between conventional SHM and emerging PBSHM. This necessitates the development of tools and techniques that promote the use of PBSHM within civil engineering industry.

One of the main challenges lies in the creation of IE models, for which there are currently limited available tools. To address this gap, this paper introduces the concept of an FE to IE model converter. The impact of this converter within the field of PBSHM has the potential to be significant as it empowers the transformation of existing FE models into their IE counterparts. By doing so, it not only mitigates the need for specialised IE model expertise, but also enhances the accessibility and ease of adoption of PBSHM.

This paper, presents a detailed procedure for converting FE models to IE models, encompassing two critical stages: the extraction of relevant information from FE models and the generation of IE models from the extracted data. The utilisation of this conversion tool holds the potential to accelerate the adoption of PBSHM by enabling the incorporation of an expansive array of structures with pre-existing FE models into the PBSHM framework.

2 IE MODEL OVERVIEW

In the second part of the 'Foundations of Population-based Structural Health Monitoring' series, (Gosliga et al., 2021) introduced the concept of an Irreducible Element (IE) model. The IE model is used in PBSHM to represent significant structural components and their interactions. It provides an abstract representation needed to assess the similarity of different structures in the network. The IE model only considers components belonging to the structure and describes where the interactions with external systems are, without providing information on how they interact with a model.

To create an Irreducible Element (IE) model, two lists are needed. The first list encompasses individual elements within a structure, each accompanied by attributes such as material and geometry. The second is a list of relationships which define how each element is connected to each other and the properties of each connection. In essence, an IE model is constructed through these two lists, encapsulating the structural elements and their relationships.

This is an oversimplification of how IE models are created and there are a lot of details that have to be considered when developing a system that is required to model structures ranging from aeroplanes to bridges. A more comprehensive description can be found in (Gosliga et al., 2021).

3 PROCEDURE FOR CONVERTING FE MODELS TO IRREDUCIBLE ELEMENT MODELS

The creation of IE models remains a challenge, as there is a limited availability of tools for their generation. To bridge the gap between conventional Structural Health Monitoring (SHM) and emerging PBSHM, we introduce the concept of a Finite Element (FE) to Irreducible Element (IE) model converter. This converter holds significant potential within the field of PBSHM, as it empowers the transformation of existing FE models into their IE counterparts. By doing so, it not only mitigates the need for specialised IE model expertise but also enhances the accessibility and ease of adoption of PBSHM in the civil infrastructure industry.

In this section, we present a detailed procedure for converting FE models to IE models, separated into two stages: the extraction of relevant information from FE models and the generation of IE models from the extracted data. The idea of this separation is that stage one would be software dependent, and stage two would be a generalised procedure that should work with any FE software. This division of the procedures means that only stage one would have to be altered if a new FE software is used to create the FE models.

3.1 *Creation of the FE model*

Before the introduction of the conversion procedure, this section provides a brief overview of how an FE model is traditionally created. In FE analysis, structures are discretised into finite elements, which are interconnected to simulate their behaviour under various loading conditions. The Finite Element (FE) software, Lusas (version 19), was used for this research. The creation of an FE model typically involves:

- Geometry and Mesh Generation: Define the geometry of the structure and generate a mesh by dividing it into finite elements.
- Material Properties: Assign material properties to the elements, including information about stiffness, density, and other mechanical characteristics.
- Boundary Conditions: Specify boundary conditions to represent how the structure interacts with its surroundings.
- Loading conditions: Specify which parts of the structure are under loading and the magnitude of this loading.

In the context of this work, the primary difference in creating FE models for conversion to IE models lies in providing the elements with human understandable names, which is required for generating IE models with meaningful structural descriptions.

3.2 *Stage one: Extracting relevant information from the FE model*

To convert an FE model into an IE model, the first stage involves the extraction of key information from the existing FE model, this information includes positional, geometrical and material information for all of the elements. This information is vital for creating an accurate representation of the structure in the IE model. This information is required for any FE simulation and so the only unknown between different FE software is how this information can be extracted from the model. For this research, LUSAS version 19 software was used. After the model had been created in LUSAS there are a number of exported formats, two formats were selected as they contain all the required information. These were a Visual Basic for Applications (VBA) Script File and an Industry Foundation Classes (IFC). These are both common text-based file formats and the latter being an open file format used by Building Information Modelling (BIM) programs. These files were then parsed using Matlab and grouped into the following tables:

Regular Element Information

Contains data related to elements within the FE model that are the 'regular elements' within the IE model, including element name, element type (line/surface), geometry reference, material reference and the coordinates of the vertices. The vertices of a line are the two end points and the vertices of a surface are the 4 corner points.

Ground Element Information

Ground elements are unique to IE models and comprise unique element names to denote the location of where the model interacts with other external systems. At this stage of the process, the location of the support conditions within the FE model are recorded to create a list of equivalent ground elements with unique names.

Relationship Information

This table takes the vertices stored in the 'Regular Element' table and uses the shared vertices to determine which elements are connected to each other. By default, the connections are fully static within the FE model and so that is the default relationship that is defined in the IE model. At this point in the procedure, the algorithm determines which connections are 'perfect'. Perfect relationships within an IE model are defined as 'A relationship that represents the interaction between two elements where the two elements in question could be considered to be the same singular element'. To determine whether there is a perfect relationship there are two tests one for line elements and one for surface elements. For lines, if geometry matches and the lines are connected and parallel (to a defined tolerance), there is a perfect relationship.

For surfaces, if geometry matches and the surfaces share an edge there is a perfect relationship. For the relationships that are determined to be perfect, they are suffixed with an '_P' so they can be identified at a later stage.

Boundary Condition Information

Specifies the support conditions and locations of the boundary conditions applied to the model, such as fully fixed or pinned. These properties while not utilised in the current version of IE models may be implemented in future revisions.

Geometry Information

Includes geometric properties of the elements within the FE model, defining dimensions, shape, and spatial arrangement. At this point, the geometry of each element is matched to a predefined list of allowed geometry types in the IE model schema.

Material Information

Provides data on material properties assigned to each element, encompassing stiffness, density, and other mechanical characteristics. Again, like the geometry information, each unique material is matched to a predefined list of allowed material types in the IE model schema.

General Model Data Information

This table extracts the model properties of the FE model such as the units that are used for dimensions, loads etc and the vertical direction defined in the model.

These tables collectively constitute a comprehensive dataset that captures the essential characteristics of the FE model. The grouping of information into these categories facilitates a systematic and organised approach to the subsequent stages of IE model generation. Stage two in the process involves utilising this extracted information to generate an IE model in the specific format that is required by the IE model schema.

3.3 *Stage two: Generating IE model from extracted information*

Once the relevant information is extracted from the FE model, the second stage involves generating an IE model based on the extracted data. IE models are stored using a Javascript Object Notation (JSON) format. The conversion tool formats all of the information that is described in this section into the correct JSON format as outlined below. This stage includes; defining the structure properties and then defining the IE model section properties, which comprise the type of model, the elements in the model and the relationships between the elements.

Defining Structure Properties

To define the structure properties, three items are needed, the name of the structure, the population that the structure belongs to and the timestamp as to when the model is created. The name and the population field are user inputs, and the algorithm produces the timestamp in the correct format based on the clock of the system being used.

Defining the IE model

The first aspect of the IE model that needs to be defined is the type. This can be either 'free' or 'grounded'. The difference between these types is that the grounded model considers the boundary conditions and the free model does not. The type is selected by the user and if 'free' the information collected regarding the boundary conditions is ignored and if 'grounded', then the boundary condition information is incorporated into the IE model in the sequential steps.

Compiling the elements object

The elements object in an IE model is a list of both ground elements (assuming a 'grounded' model is being created) and regular elements with associated attributes. For the ground elements, the only information required is the name of the ground element a list of which has already been populated in stage one. Therefore, at this point, all that is required is collating all the ground elements in the correct format and adding the 'ground' type to each element.

The regular elements required more information than the ground elements to be valid against the current IE model schema. At a minimum, each regular element in the IE model requires the following information: name, type, contextual, geometry and material. The name and type information are straightforward as the names are extracted from the FE model and the tables extracted during stage 1 have already been separated into either 'ground' or 'regular'.

Further processing of the information extracted during stage 1 needs to be undertaken to determine the contextual, geometry and material properties needed for the regular elements.

The first step is to further divide the regular elements into line objects and surface objects depending on how they have been represented in the FE model. For the line objects the coordinates of the endpoints are used to calculate the length of the line and the vector of the line (compared with the global axis of the FE model). The vector of the line is used to select the context of the element from a predefined list which includes; ‘beam’, ‘column’, ‘slab’, ‘cable’ and other such contextual entities. The conversion tool has a series of rules to select the most appropriate context such as if a line object is parallel to the ground then its context is a ‘beam’ if perpendicular to the ground then its context is a ‘column’. A similar procedure is then used for the surface elements, the vertices of the surface are used to calculate the centre of the surface and the lengths of each side of the surface. This information, along with other inbuilt rules, is then used to select the most suitable contextual information from the predefined list.

For the geometry properties of the regular elements there needs to be a map of how the geometry of the FE model translates to the allowable geometry type of the IE model schema. For example a ‘Rectangular Solid’ will be mapped to the IE model type ‘beam > rectangular’ and a ‘Surface’ geometry ID in the FE model will map to a ‘plate > rectangular’ IE model type. The most common types have been mapped in the conversion tool and new items will be added as they arise further into the development.

The material properties are handled in a similar way with a map embedded into the conversion tool that translates a FE material ID to an allowable IE material.

4 ILLUSTRATIVE CASE STUDY

To demonstrate the application of the Finite Element (FE) to Irreducible Element (IE) model conversion process, this section presents a case study featuring a simple bridge structure. This example structure was designed to contain a range of common bridge elements and a range of materials thus showing the range of capabilities of the conversion procedure.

4.1 *Description of structure*

A simple bridge was chosen to have key features of typical of real-world bridges while remaining simple enough to test all the features of the conversion tool without the complexity of a real bridge. While the bridge used here would be unrealistic in the real world it does provide a mix of material and geometric features that show the capabilities of the conversion tool. The bridge has a length of 10 meters and a width of 3 meters. Concrete columns, each with a 500 mm diameter and a height of 2 meters, are located at the four corners of the deck. The bridge deck consists of a 50 mm thick steel surface and is supported by rectangular concrete beams measuring 300 mm in height and 150 mm in width. Three transverse beams span the width of the bridge, and two longitudinal beams running along the deck’s length. A schematic of the bridge can be seen in Figure 1.

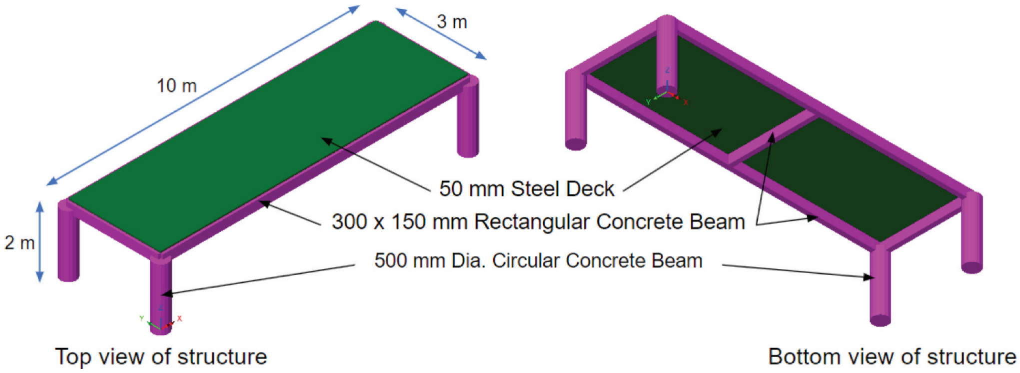


Figure 1. Schematic of simple bridge structure.

4.2 *Simple bridge FE model*

The Finite Element (FE) model of the simple bridge structure described above can be created in the conventional manner. The process involves defining the finite element mesh, geometric dimensions, assigning material properties, and specifying boundary conditions to simulate the structure as accurately as possible. It is noteworthy that creating the FE model for use with the Irreducible Element (IE) conversion tool involves minimal deviation from standard practices.

The key departure lies in the embedding of IE model element names during the creation of the FE model. This step is crucial for ensuring that the subsequent IE model, generated through the conversion process, retains human-understandable names for each element. This adjustment to the FE model means that no additional information is needed by the conversion tool. If this naming of the elements was moved to the conversion tool then the FE model would require no adjustment but the conversion tool would require more user inputs. Figure 2 shows the naming convention used for this simple structure.

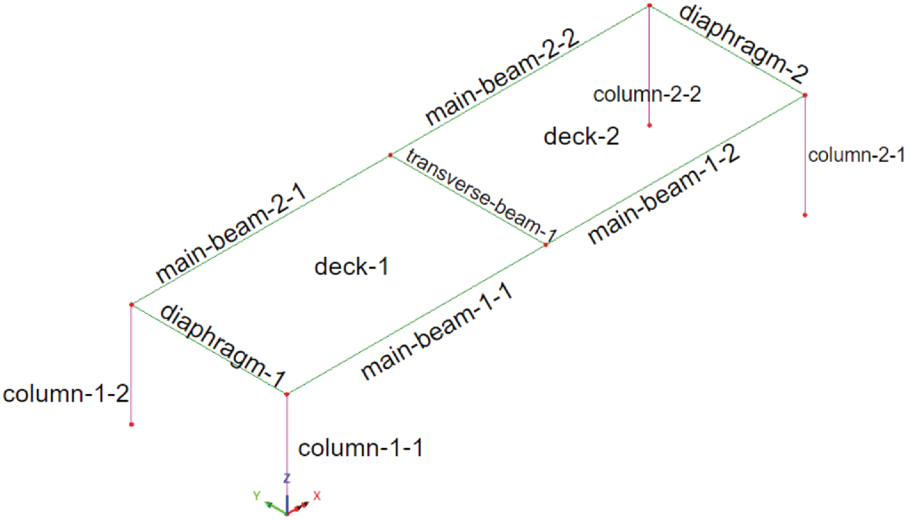


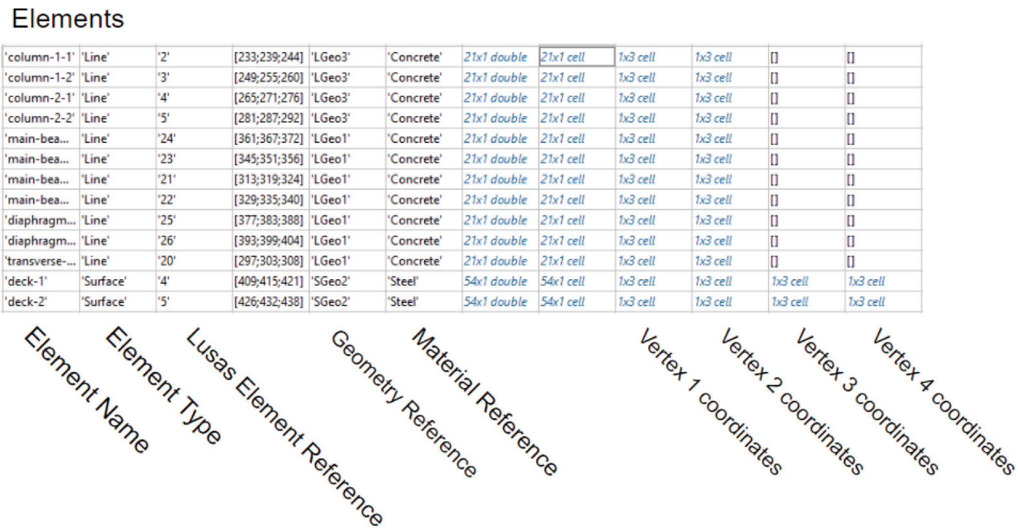
Figure 2. IE naming convention used for simple bridge structure.

Furthermore, the FE model serves another purpose during its creation. Beyond preparing for the IE conversion, it becomes a valuable tool for ensuring the structural behaviour of the model is as intended by the modeller. Deflections, obtained through the FE model, can be cross-referenced against theoretical calculations. Additionally, the model allows for the examination of the bending moment diagram and shear force diagram, providing a means to verify if the structure behaves as expected under various loading conditions. This gives a level of confidence that the structure has been modelled as intended.

4.3 *Application of the FE to IE converter*

4.3.1 *Extraction of relevant information*

After creating the FE model and checking the behaviour of the structure is as expected, the two required files can be exported from the Lusas software. Utilising the previously described in Section 3.2, the relevant information from the FE model is extracted and organised into tables, including Regular Element Information, Ground Element Information, Relationship Information, Boundary Condition Information, Geometry Information, Material Information, and General Modal Data Information. The 'Elements' tables showing the extracted information from the FE model can be seen in Figure 3, with the most significant columns labelled underneath the tables.



Elements

Element Name	Element Type	Lusas Element Reference		Geometry Reference	Material Reference			Vertex 1 coordinates	Vertex 2 coordinates	Vertex 3 coordinates	Vertex 4 coordinates
'column-1-1'	'Line'	'2'	[233;239;244]	'LGeo3'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'column-1-2'	'Line'	'3'	[249;255;260]	'LGeo3'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'column-2-1'	'Line'	'4'	[265;271;276]	'LGeo3'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'column-2-2'	'Line'	'5'	[281;287;292]	'LGeo3'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'main-bea...	'Line'	'24'	[361;367;372]	'LGeo1'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'main-bea...	'Line'	'23'	[345;351;356]	'LGeo1'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'main-bea...	'Line'	'21'	[313;319;324]	'LGeo1'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'main-bea...	'Line'	'22'	[329;335;340]	'LGeo1'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'diaphragm...	'Line'	'25'	[377;383;388]	'LGeo1'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'diaphragm...	'Line'	'26'	[393;399;404]	'LGeo1'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'transverse-...	'Line'	'20'	[297;303;308]	'LGeo1'	'Concrete'	21x1 double	21x1 cell	1x3 cell	1x3 cell	[]	[]
'deck-1'	'Surface'	'4'	[409;415;421]	'SGeo2'	'Steel'	54x1 double	54x1 cell	1x3 cell	1x3 cell	1x3 cell	1x3 cell
'deck-2'	'Surface'	'5'	[426;432;438]	'SGeo2'	'Steel'	54x1 double	54x1 cell	1x3 cell	1x3 cell	1x3 cell	1x3 cell

Figure 3. Elements table extracted from FE models.

4.3.2 *Generation of IE model*

The extracted information is then processed through the FE to IE converter. The converter transforms the FE data into an Irreducible Element (IE) model using the process outlined in Section 3.3. The generation of the Irreducible Element (IE) requires very limited additional input (structure name and population) from the user beyond the extracted information from the FE model. All pertinent information easily embedded into the IE model is automatically included, allowing a high level of adaptability to future developments of the IE model and similarity comparisons. This approach goes beyond the minimal requirements of the IE model schema, providing a degree of future-proofing by capturing additional data that may prove valuable in evolving applications of the IE models.

Furthermore, the simplicity and efficiency of this conversion process enable easy iteration. In the event of amendments or updates to the FE model, the IE model generation can be repeated with little effort. This adaptability ensures that any modifications made to the underlying structure are seamlessly reflected in the corresponding IE model. The iterative nature of the conversion process allows any changes to the structure in real life to be reflected in the IE model, promoting a dynamic and responsive workflow for ongoing structural health monitoring processes. Figure 4 shows the attributed graph constructed using the IE model file. This graph is a simple form of validation, letting the user easily see if the elements of the IE model are in the correct location.

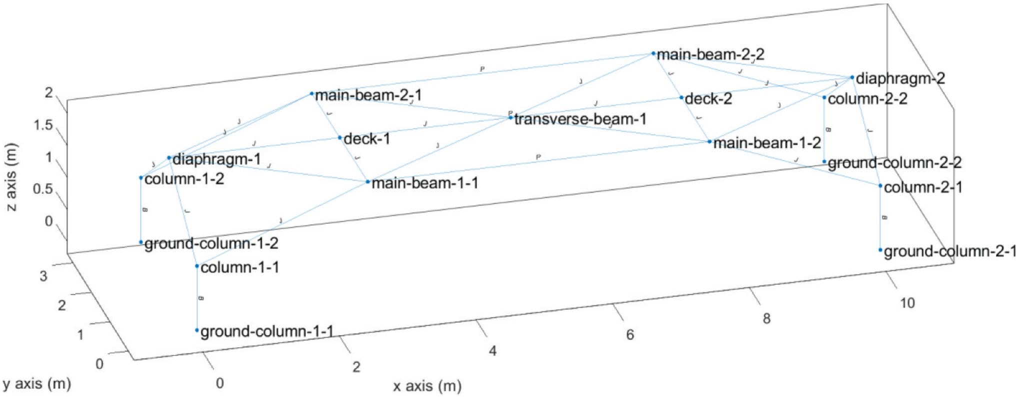


Figure 4. Attributed graph constructed from IE model.

5 CONCLUSION

In addressing the challenges posed by Population-Based Structural Health Monitoring (PBSHM) and the need for effective knowledge transfer among structures within a population, this paper has presented a novel approach through the development of a Finite Element (FE) to Irreducible Element (IE) model conversion tool. The research problem centred around the limitations in existing tools for creating IE models with the aim to bridge the gap between more traditional engineering models (FE) and the new technology of the IE model which can offer population based intelligence for informed decision making by asset owners. The outlined procedure for converting FE models to IE counterparts offers a systematic and accessible solution to developing IE models. The conversion tool was designed to operate with FE models created through standard practices with minimal required amendments to the FE model. The benefits of the FE to IE conversion tool extend beyond mitigating the need for specialised IE model expertise. By encapsulating essential structural information, the tool facilitates the incorporation of an expansive array of structures into the PBSHM framework, thereby accelerating the adoption of PBSHM in the civil infrastructure industry. The creation of an FE model prior to an IE model also has the benefit of allowing checks to be made to the behaviour of the structure. The implications of this conversion tool on PBSHM are significant. It provides a practical means to establish structural similarities among diverse members of a population which is essential in preventing negative transfer effects and enabling more effective knowledge transfer within the PBSHM framework.

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