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(54) **SYSTEMS AND METHODS FOR THE ASSESSMENT OF FATIGUE STRENGTH OF CELLULAR STRUCTURES**

(71) Applicant: **GE Avio S.r.l.**, Rivalta di Torino (IT)

(72) Inventors: **Simone Romano**, Orbassano (IT); **Edoardo Maria Peradotto**, Torino (IT); **Cesare Stranges**, Turin (IT); **Stefano Foletti**, San Colombano al Lambro (IT); **Matteo Gavazzoni**, Locate di Triulzi (IT); **Stefano Beretta**, Voghera (IT)

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(57) **ABSTRACT**

Systems and method are provided for predicting an expected mechanical property, such as fatigue strength, for a component with a cellular structure or a portion thereof. In some embodiments, a method for predicting fatigue strength includes receiving, by a control circuit, image data for a specimen to reconstruct 3D models of the specimen. The specimen includes at least one cell of a cellular structure. The method further includes determining a local stresses for the specimen via finite element analysis of the three-dimensional models. The control circuit may then determine a fatigue strength for the specimen based on the local stresses to generate a distribution function of the fatigue strength for the at least one cell of the cellular structure. The control circuit then applies statistics of extremes to the distribution function to predict an expected fatigue strength of a number of cells in the cellular structure.

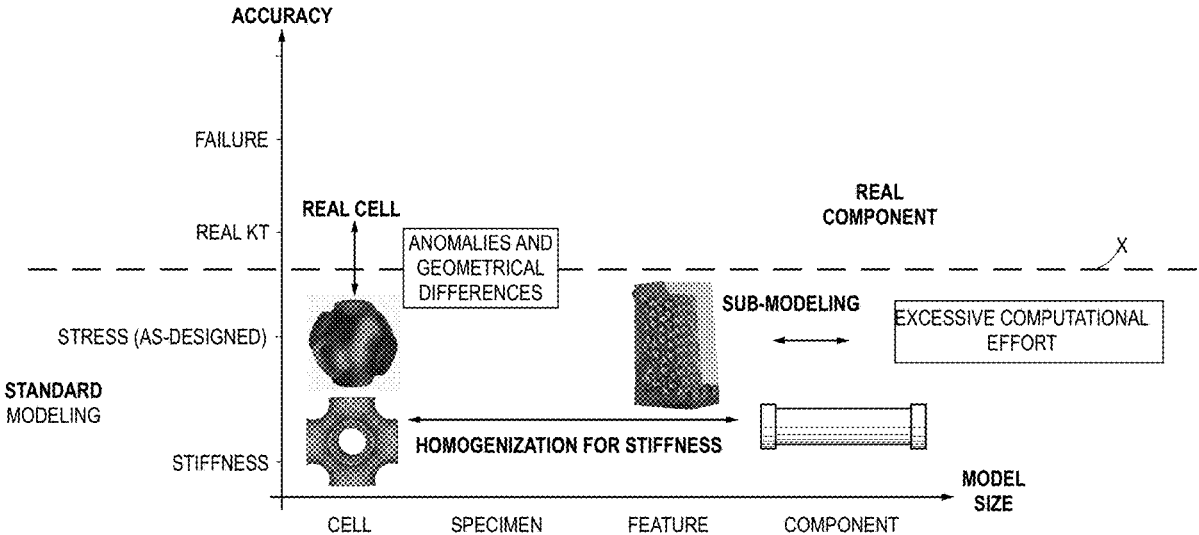


FIG. 1A

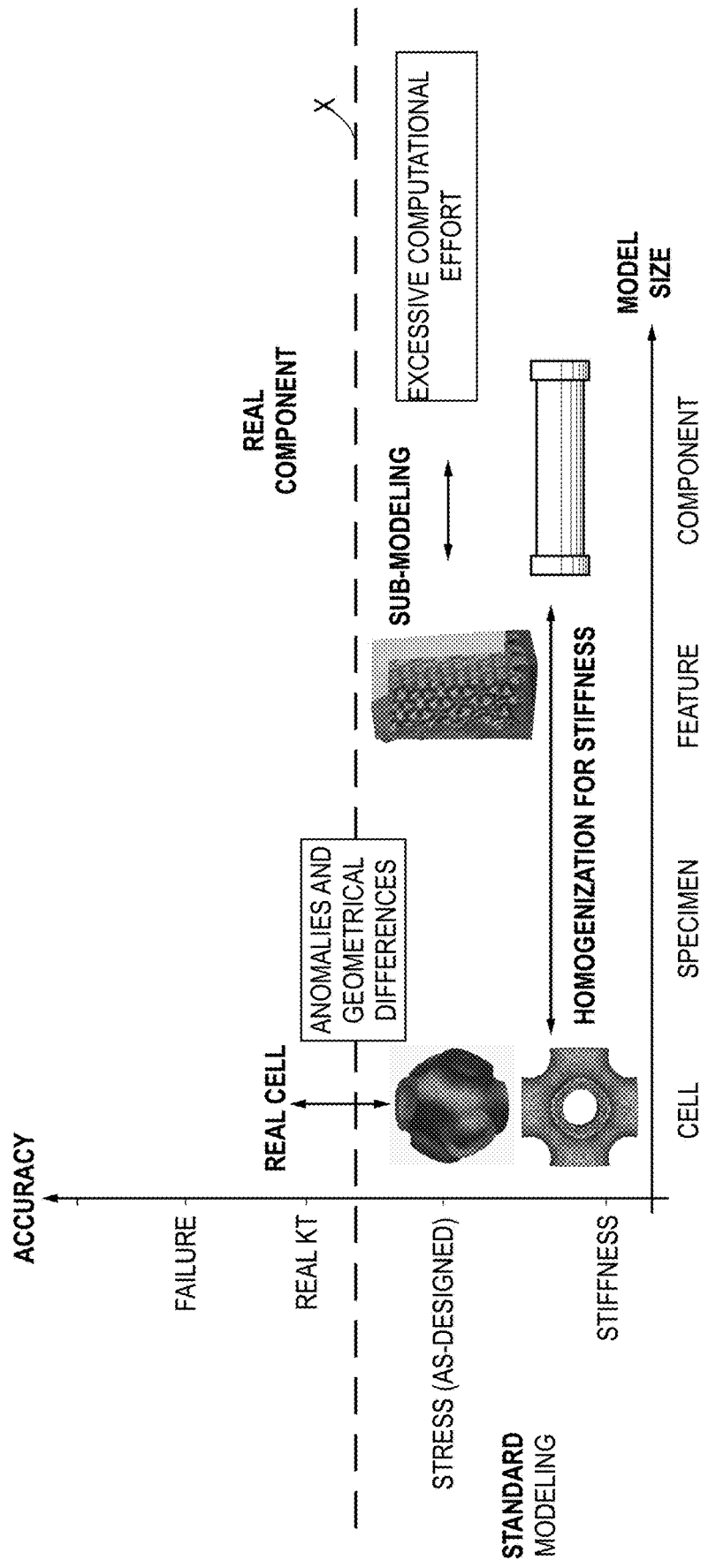


FIG. 1B

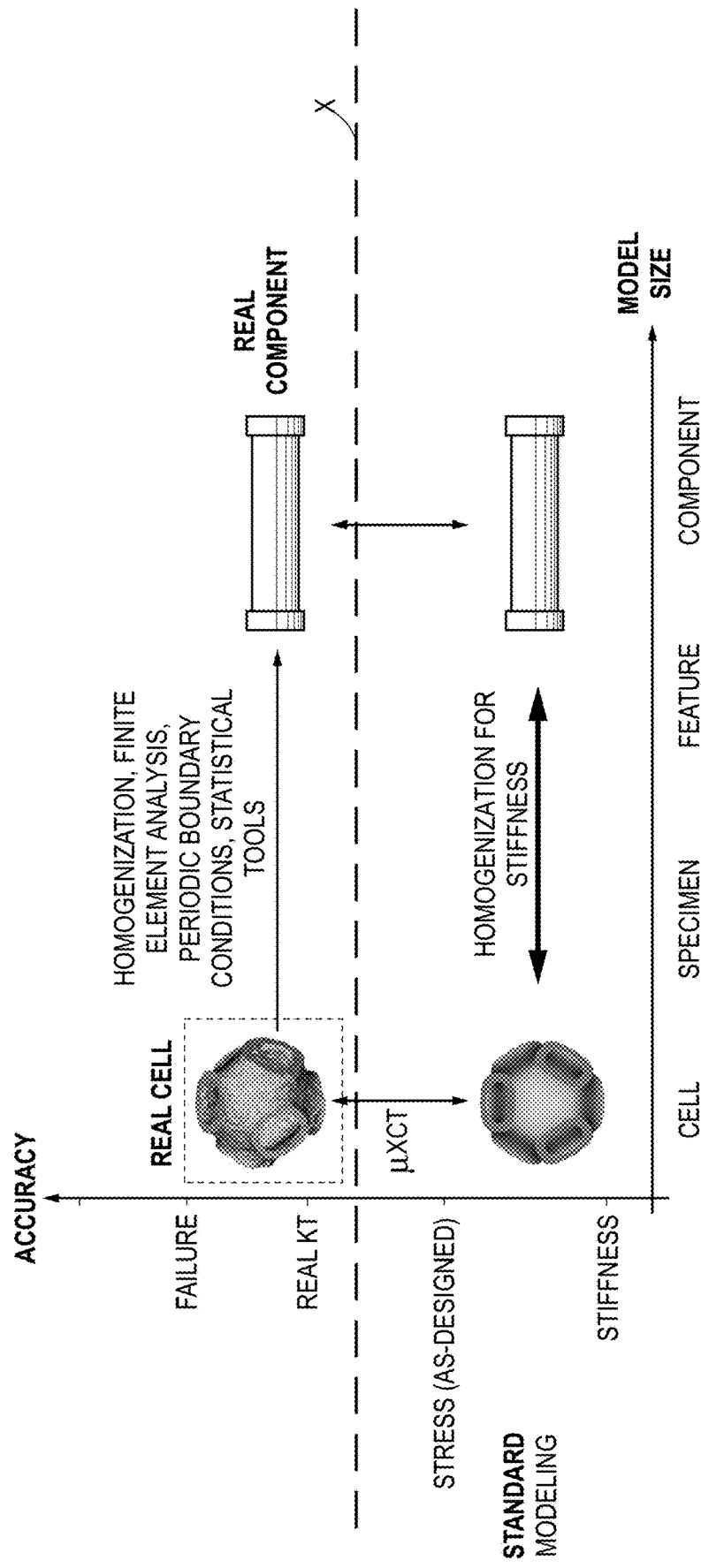


FIG. 2

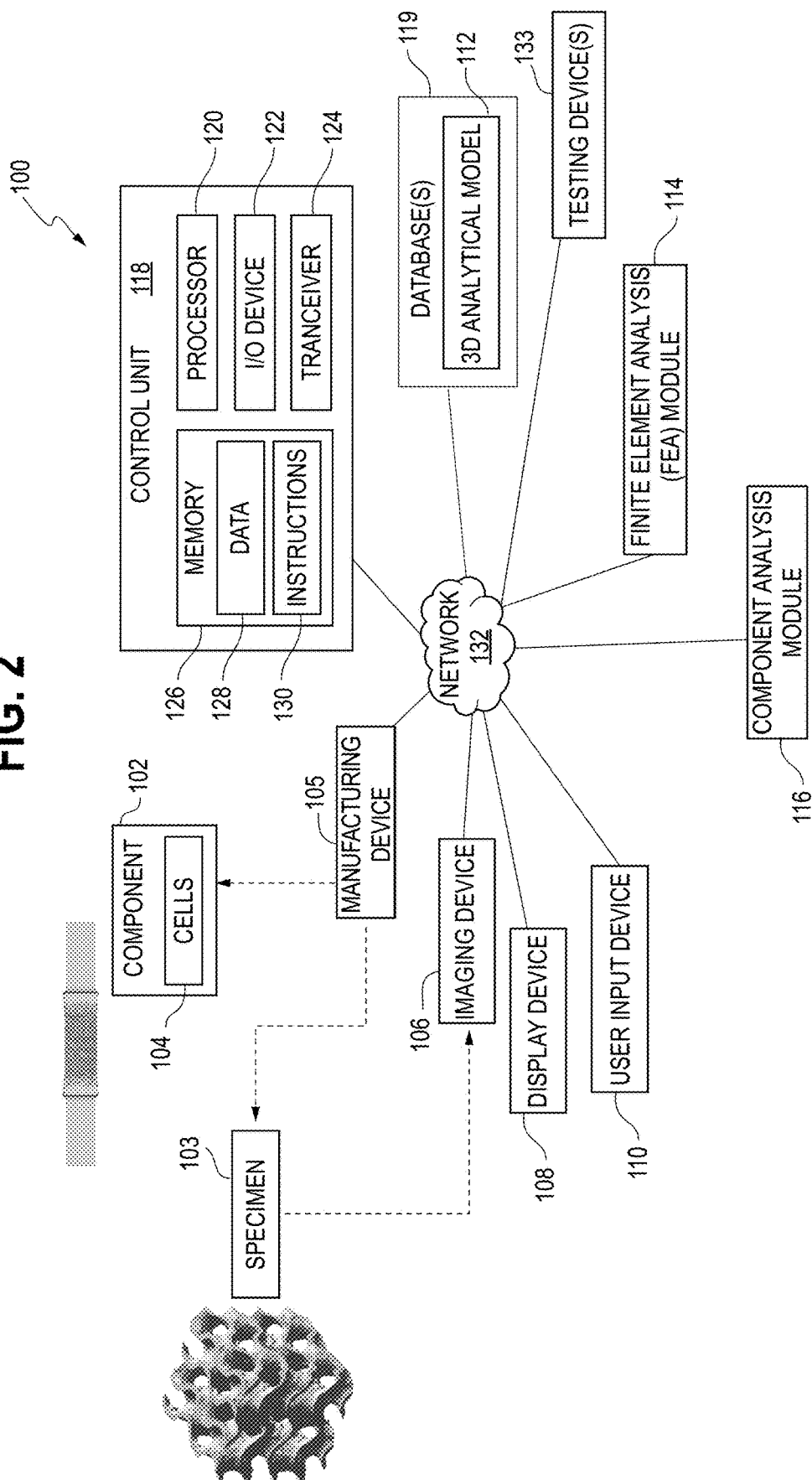


FIG. 3

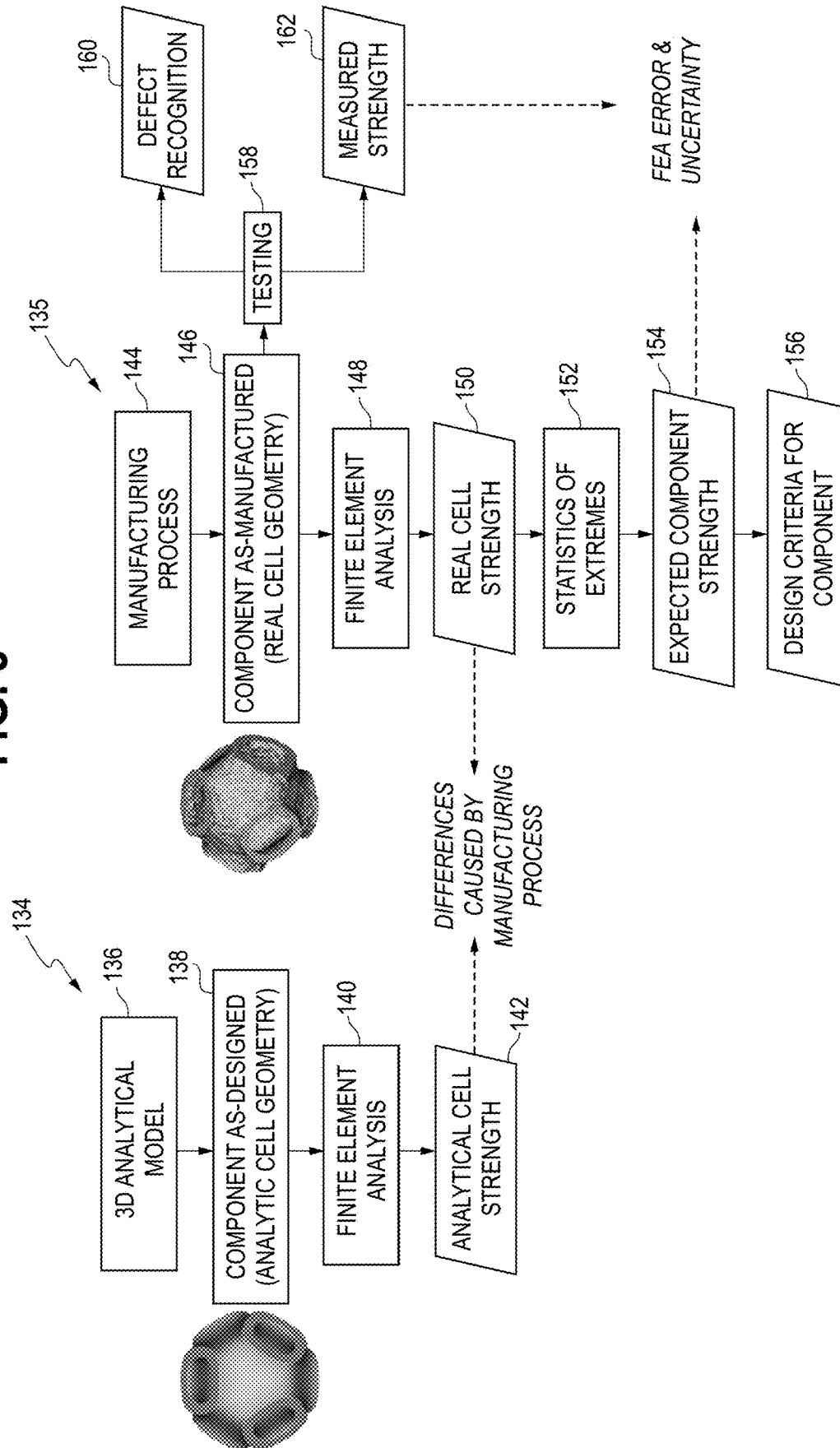


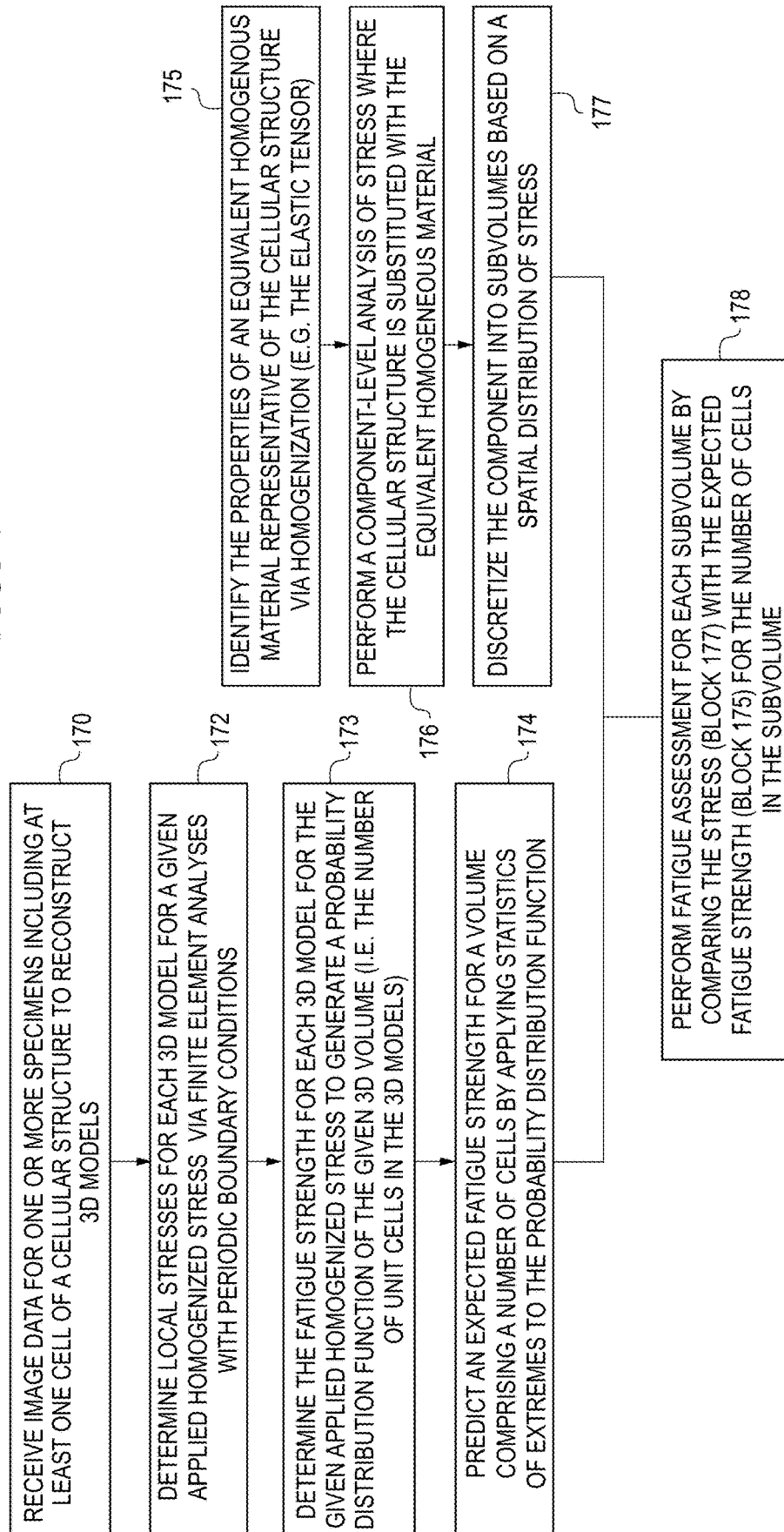
FIG. 4

FIG. 5

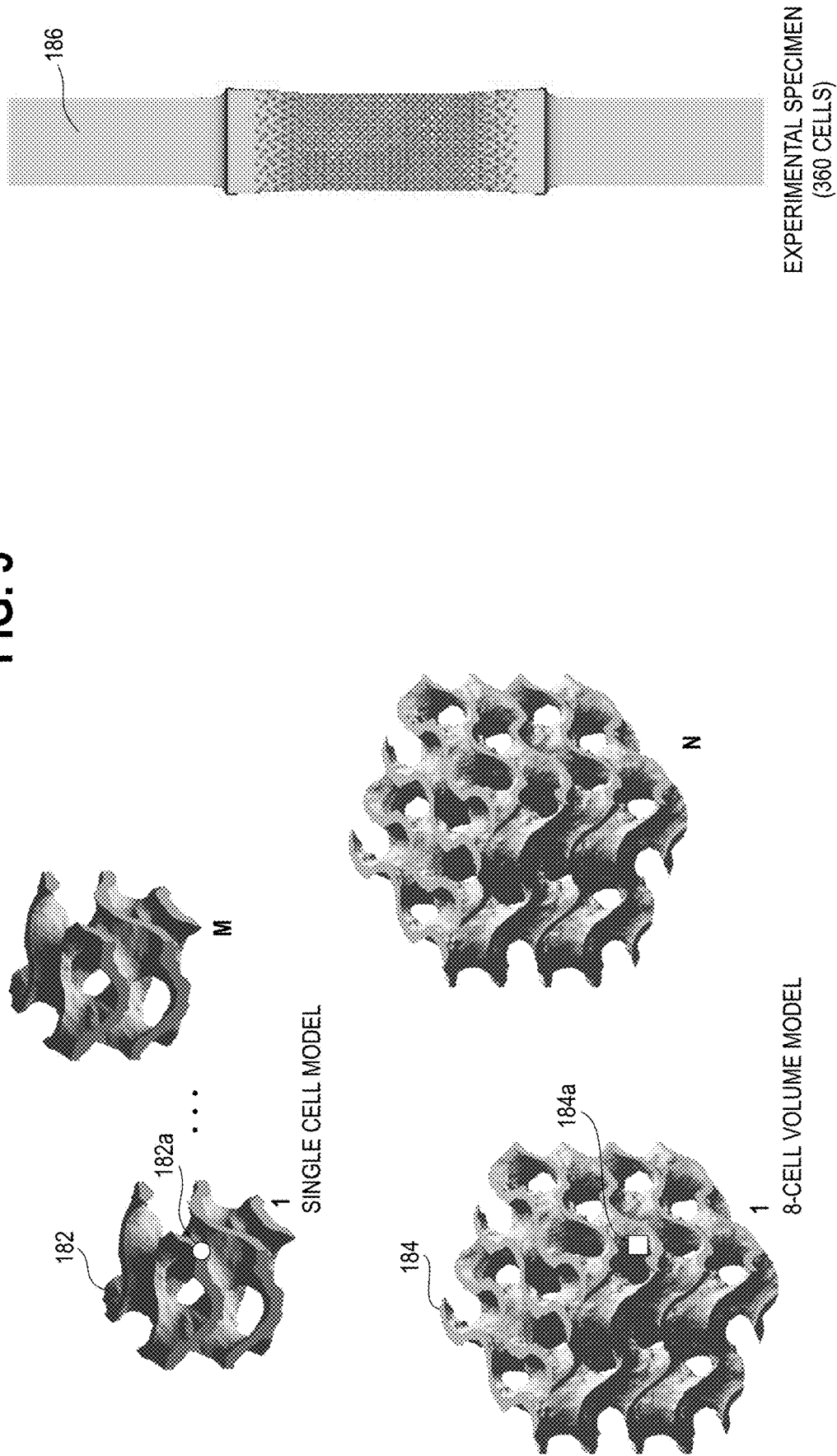


FIG. 6

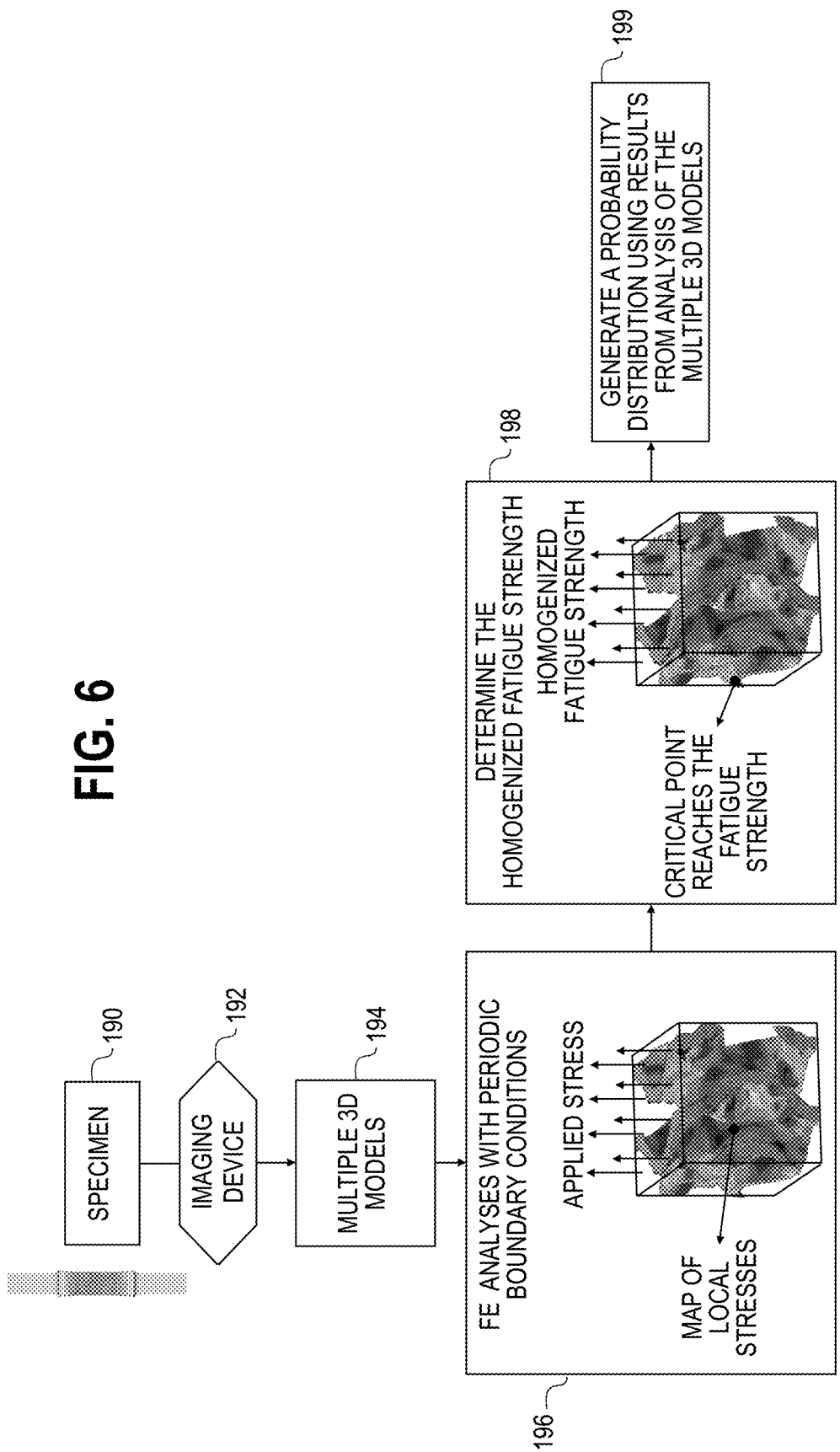


FIG. 7

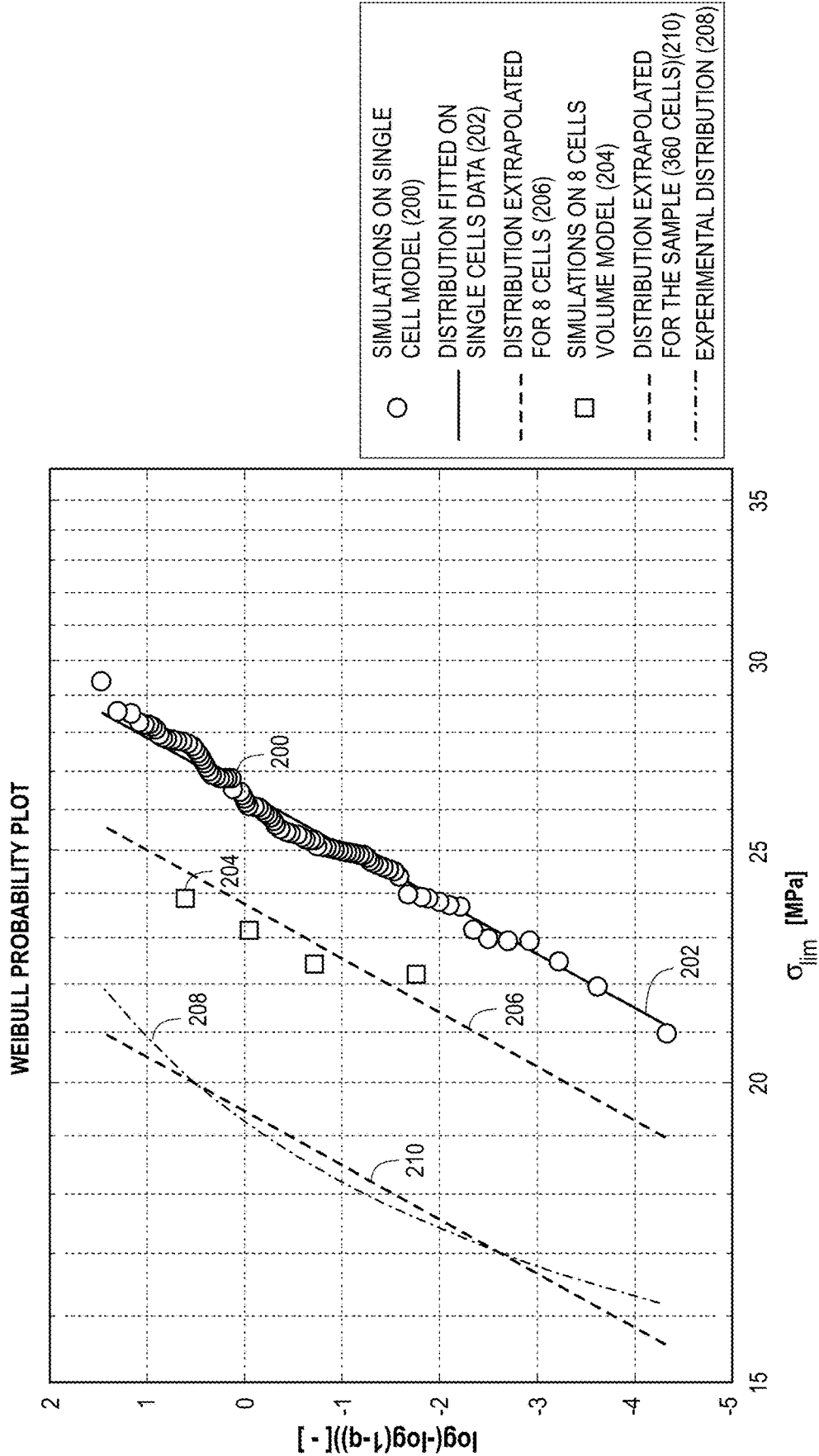


FIG. 8

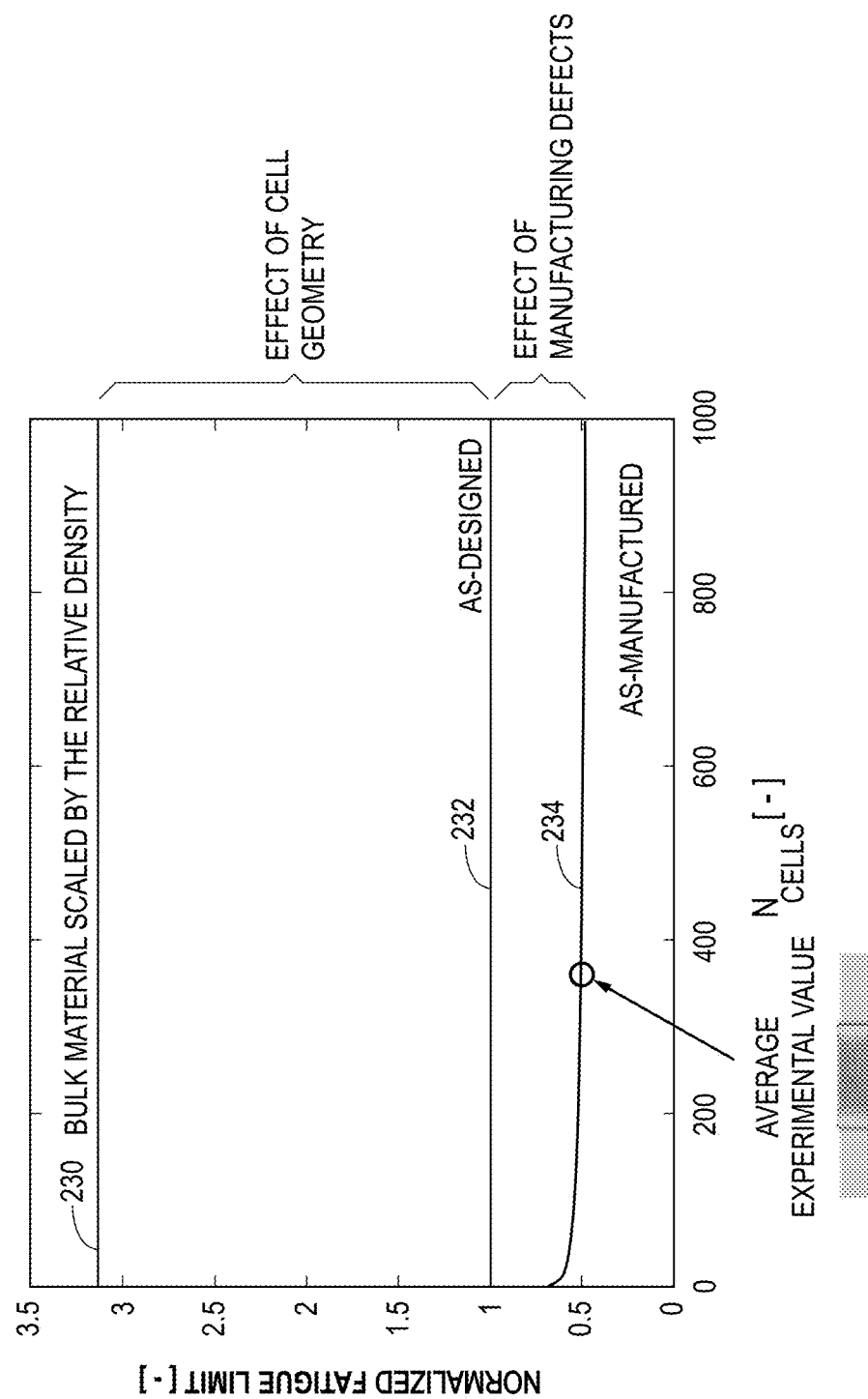


FIG. 9B

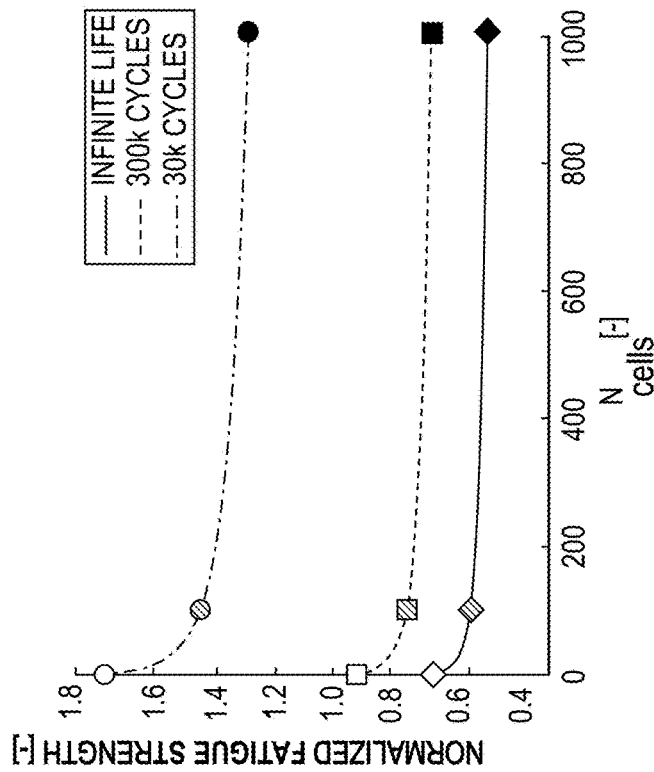
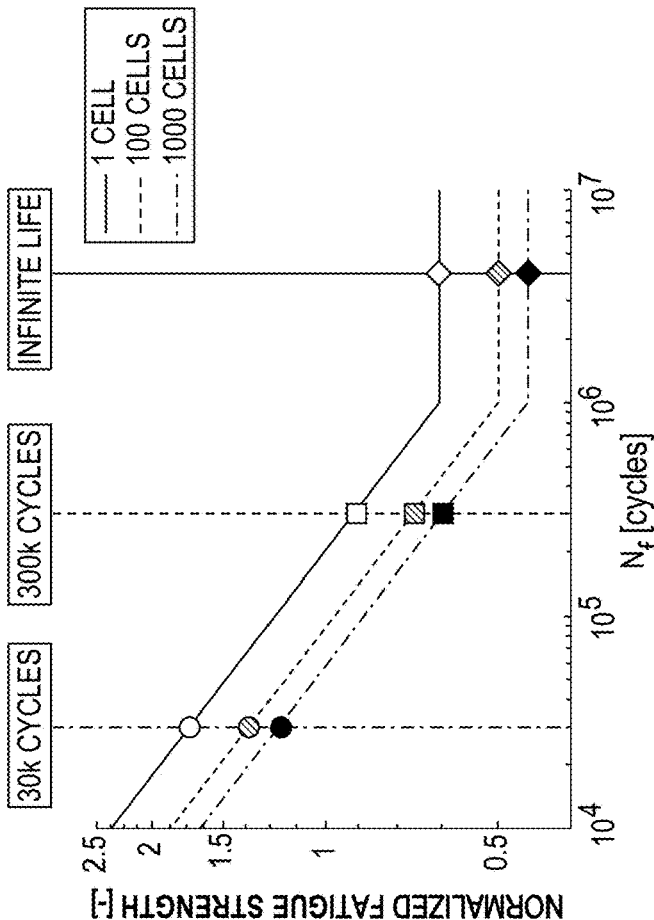


FIG. 9A



SYSTEMS AND METHODS FOR THE ASSESSMENT OF FATIGUE STRENGTH OF CELLULAR STRUCTURES

TECHNICAL FIELD

[0001] These teachings relate generally to cellular structures, and, more particularly to the assessment of fatigue strength for components having cellular structures.

BACKGROUND

[0002] Additive manufacturing and other manufacturing techniques provide the ability to produce components having complex structures such as structures with three-dimensional cellular structures. Such cellular structures include a three-dimensional arrangement of repeating cells to create a continuum. Components comprising cellular structures may be subjected to different stresses and loadings during use. Accordingly, it may be useful to evaluate the mechanical properties, such as the fatigue strength, of components having cellular structures to understand their structural integrity and mechanical behavior.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] Various needs are at least partially met through provision of the systems and methods for the assessment of fatigue strength of components described in the following detailed description, particularly when studied in conjunction with the drawings. A full and enabling disclosure of the aspects of the present description, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which refers to the appended figures, in which:

[0004] FIG. 1A comprises a graphical depiction of a typical approach for assessing fatigue strength for a component;

[0005] FIG. 1B comprises a graphical depiction of approaches for assessing fatigue strength for a component in accordance with various embodiments of these teachings;

[0006] FIG. 2 comprises a schematic diagram of a system for assessing fatigue strength for a component in accordance with various embodiments of these teachings;

[0007] FIG. 3 comprises a flow diagram of an approach for assessing fatigue strength in accordance with various embodiments of these teachings;

[0008] FIG. 4 comprises a flow diagram of a method in accordance with various embodiments of these teachings;

[0009] FIG. 5 comprises exemplary specimens that may be employed in the method of FIG. 4 in accordance with various embodiments of these teachings;

[0010] FIG. 6 comprises a flow diagram of an approach for generating a probability distribution function for a given volume of a cellular structure in accordance with various embodiments of these teachings;

[0011] FIG. 7 comprises probability plots for the fatigue limit (σ_{lim}) of a single cell, a 8-cell volume, and an exemplary fatigue specimen in accordance with various embodiments of these teachings;

[0012] FIG. 8 comprises a graphical overview of an application of the methods described herein showing fatigue strength as a function of a number of cells in accordance with various embodiments of these teachings; and

[0013] FIG. 9A comprises an exemplary graph of fatigue strength in accordance with various embodiments of these teachings.

[0014] FIG. 9B comprises an exemplary graph of fatigue stress in accordance with various embodiments of these teachings.

[0015] Elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions and/or relative positioning of some of the elements in the figures may be exaggerated relative to other elements to help to improve understanding of various embodiments of the present teachings. Also, common but well-understood elements that are useful or necessary in a commercially feasible embodiment are often not depicted in order to facilitate a less obstructed view of these various embodiments of the present teachings. Certain actions and/or steps may be described or depicted in a particular order of occurrence while those skilled in the art will understand that such specificity with respect to sequence is not actually required.

DETAILED DESCRIPTION

[0016] Various aspects of the present disclosure may be employed to predict the fatigue strength of components or portions thereof having cellular structures. The systems and methods described herein provide robust and computationally feasible approaches for the assessment of additively manufactured metamaterials having cellular structures. The systems and methods of determining fatigue strength apply homogenization, finite element analysis with periodic boundary conditions, and statistical tools to reduce the computational effort involved with evaluating a cellular structure and capture the effects of the real cell geometry in order to assess a predicted stress state and strength of a real or as manufactured component.

[0017] Because cellular structures may include a large number of repeating cells, an assessment of mechanical properties, such as fatigue strength, for a component comprising a cellular structure employs a large number of nodes in finite element analysis (FEA) simulations. Thus, finite element analysis (FEA) simulations performed on analytic cell geometries of such cellular structures may require large computational effort and large computational power and/or time to analyze a full-scale component. Further, additive manufacturing processes used to manufacture the cellular structure can introduce inaccuracies and/or anomalies that make prediction of the fatigue strengths of as-manufactured parts challenging. Differences between analytic models of a component and the real-world component due to the effects of the manufacturing process, may result in differences between modeled stresses and stresses observed in the real-world. These are all significant challenges in the context of assessing fatigue strength for a component having a cellular structure with repeating cells.

[0018] Fatigue strength, as used herein, refers to the fatigue strength along any portion of an S-N diagram. The S-N diagram defines the number of cycles to failure, N_{cycles} , when a material is repeatedly cycled through a given stress range, S . Thus, the fatigue strength includes both finite life region (e.g., regions with low cycle fatigue and high cycle fatigue) and infinite life region (e.g., the region where if stress levels are below a certain level, an infinite number of cycles can be applied without causing a failure) on the S-N diagram. Accordingly, the fatigue

strength as referred to herein may be the fatigue limit for a material, though it is not limited thereto. Exemplary S-N diagrams are depicted, for example, in FIGS. 9A and 9B.

[0019] Generally speaking, the various aspects of the present disclosure can be employed to predict the fatigue strength of components with cellular structures. Cellular structures may include but are not limited to, for example, lattices structures or triply periodic minimal surfaces (TPMS) cell structures. Such components may be manufactured, for example, via additive manufacturing processes. The systems and methods described herein use a combination of homogenization with statistical tools to represent the variability of the fatigue strength for a given volume composed by a finite number of cells. The approaches described herein use a CT scan, such as an x-ray micro computed tomography (μ CT) scan, of from a subset of cells in a given volume of a component to reduce the computational efforts involved with prior approaches. There are also limitations (e.g., small voxel size from CT scans) to prior approaches that involve the analysis of the full-scale component that limit the accuracy of such approaches. Rather than evaluating a CT scan of the entire volume of the component, the fatigue strength of a subset of cells may be evaluated and results applied to the given volume via homogenization. The statistical tools employed are based on statistics of extremes that infers the fatigue strength of the entire volume of the component, or any number of cells subjected to high stress, based on CT scan of a subset of cells within the volume and finite element analysis of 3D image data acquired from the CT scan. The approaches also apply periodic boundary conditions to further reduce the computational effort and avoid edge effects.

[0020] The approaches of assessing fatigue strength provided herein may provide a robust prediction of fatigue strength for metamaterials having a cellular structure at the early stage of design without the need for complex and expensive testing campaigns. The approaches may eliminate or reduce the need for extensive material testing as the approaches utilize CT scans of a subset of cells and finite element analysis. Thus, the approaches for assessing fatigue strength for a component described herein may reduce component development cost, reduce the lead time for development, and increase confidence in design results.

[0021] The approaches described herein may also be adopted to compare components manufactured using different manufacturing conditions such as, different machines, parameters, pre-processing, post-processing, etc. For example, manufacturing parameters may be adjusted to obtain a specimen. The cells may then be scanned using μ CT, the geometry of the cells reconstructed, and finite element analysis performed on the reconstructed cells in order to assess the fatigue strength of the specimen. The fatigue strength of the component may then be assessed based on the fatigue strength of the specimen. When the manufacturing process is an additive manufacturing process, a large number of inputs or parameters may be adjusted and may affect the resulting component strength. Testing any possible change to such inputs or parameters may not be a possibility or may be expensive and time-consuming. Assessing component strength via the approaches described herein may facilitate the evaluation of expected fatigue strength for a component in a cheaper and less time-consuming manner.

[0022] The approaches herein may be applied to components having cellular structures, such as lattice structures, or other structures having a repeating cell structure. Some examples of such components include, but are not limited to, components having gyroid, diamond, or trifurcating unit cells.

[0023] FIG. 1A provides a graphical depiction of a typical approach for assessing fatigue strength for an additively manufactured part having a cellular structure. The x-axis on the graphical depiction represents model size, ranging from a cell-level model to a component-level model. A cell-level model captures a single unit cell within the cellular structure of a component. A specimen-level model captures a number of cells in the component. A feature-level model captures a portion of the component. A component-level model captures the entire or a majority of the component. The y-axis depicts the model accuracy.

[0024] The accuracy below line “X” is what can be accomplished for assessing fatigue strength via standard modeling. Typical approaches that involve standard modeling may evaluate material stiffness and stress (as-designed). However, standard modeling may not be able to assess the real stress concentration factor (K_t), which quantifies how concentrated the stress is in a mechanical part. Nor can standard modeling assess or predict structural failure (e.g., when the material is stressed to its strength limit, causing fracture or excessive deformation) or functional failure (e.g., the inability of the material to fulfill an intended function to a standard performance). The accuracy limits of standard modeling may be limited, for example, by the inability to capture anomalies or geometrical difference between unit cells of the cellular structure as-designed and as-manufactured.

[0025] Referring still to FIG. 1A, typical approaches for assessing fatigue strength for a cellular structure may involve constructing a three-dimensional (3D) analytical model of a unit cell of the component to assess stiffness. The component is then homogenized for stiffness, that is, stiffness of the unit cell is applied to a larger volume of component, for example, the portion of the component including cells. Sub-models may then be constructed for individual features of the component in order to evaluate the stress applied to the feature (as-designed). Sub-models may include the detailed 3D mesh and nodes that are involved in order to model the cellular structure of the feature. Modeling the cellular structure of the entire component under typical approaches may be prohibitive as it involves excessive computational effort due to the number of nodes involved in describing the 3D shape of the cellular structure with the required level of accuracy. Further, the 3D analytical model of the unit cell may not capture anomalies and geometrical differences in the real cell.

[0026] FIG. 1B provides a graphical depiction of the approaches provided herein for predicting fatigue strength for an additively manufactured component having a cellular structure. The x-axis and y-axis are the same as those described with reference to FIG. 1A. The approaches provided herein use imaging data, such as data from a computed tomography (CT) scan, of the real unit cell geometry of a cellular structure (e.g., an image of a specimen that includes the unit cell or a number of cells as-manufactured). Thus, an actual 3D image or model of the real unit cell of the cellular structure may be employed to assess the stress concentration factor (K_t), for example, via finite element analysis. The

approaches provided herein may perform finite element calculations based on the structure of a real unit cell. Using finite element analysis, simulations may be performed on the real unit cell to derive real constants that define the behavior of the material. Such constants may include the elastic modulus (E), yielding stress (σ_y), ultimate strength (σ_{max}), strain at failure (ϵ_f), fatigue limit (σ_{lim}), stress concentration factor (Kt), Poisson's ratio (ν), shear modulus (G), yield locus, or similar. The real constants may then be applied to the entire component via homogenization. Using statistical tools, such as weakest link theory and statistics of extremes, and periodic boundary conditions, it is then possible to derive the fatigue strength of the component or other materials.

[0027] Using the approaches provided herein for predicting fatigue strength, it may be possible to predict the occurrence of a failure or a part failure area. The part failure area may be, for example, a region of a component that is subjected to high stress and, thus, prone to possible failure. The part failure area may also be referred to as a critical area. Further, the approaches provided herein may eliminate the need to construct a 3D analytical model of the entire or full component, which would involve a prohibitive number of nodes in the 3D mesh, or to construct a model of particular features of the component.

[0028] The terms and expressions used herein have the ordinary technical meaning as is accorded to such terms and expressions by persons skilled in the technical field as set forth above except where different specific meanings have otherwise been set forth herein. The word "or" when used herein shall be interpreted as having a disjunctive construction rather than a conjunctive construction unless otherwise specifically indicated. The terms "coupled," "fixed," "attached to," and the like refer to both direct coupling, fixing, or attaching, as well as indirect coupling, fixing, or attaching through one or more intermediate components or features, unless otherwise specified herein.

[0029] The singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise.

[0030] Approximating language, as used herein throughout the specification and claims, is applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms such as "about", "approximately", and "substantially", are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value, or the precision of the methods or machines for constructing or manufacturing the components and/or systems. For example, the approximating language may refer to being within a 10 percent margin.

[0031] The foregoing and other benefits may become clearer upon making a thorough review and study of the following detailed description. Referring now to the drawings, and in particular, to FIG. 2, a system 100 that is compatible with many of these teachings will now be presented.

[0032] The system 100 may be employed to predict fatigue strength for a component 102 as-manufactured (e.g., for the real cell geometry). The component 102 has a cellular structure with cells 104, which may also be referred to as unit cells. In some aspects, the component 102 is an addi-

tively manufactured component. In some embodiments, the component 102 is a heat exchanger of a gas turbine engine or a portion thereof. It is contemplated that the systems and methods described herein may be applied to other gas turbine engine components. However, it is to be understood that the systems and methods may also apply to other types of parts or components including a cellular structure.

[0033] The system 100 may analyze a specimen 103 that is representative of the component 102 and use such analysis results to infer the fatigue strength of the component 102 (e.g., in its entirety) as-manufactured. The specimen 103 is a real printed or manufactured cell geometry. The specimen 103 may include one or multiple cells. The specimen 103 also has a cellular structure. The specimen 103 may be representative of the component 102 in the sense that the specimen 103 has the same or a similar cell size as the component 102 and/or has the same or a similar cell geometry of the component. In some aspects, the specimen 103 may be also representative of the component 102 in the sense that the specimen 103 was manufactured using the same type of manufacturing device (e.g., a 3D printing device), under the same manufacturing conditions, was placed in the same or a similar position in the build platform during manufacturing, and/or was oriented in the same manner during manufacturing as the component 102. Thus, the specimen 103 includes a number of cells that reflect the real cell geometry of the component 102. As described in further detail below, the specimen will be scanned and reconstructed to a 3D model of the real cell geometry.

[0034] The system 100 includes a manufacturing device 105, an imaging device 106, a display device 108, a user input device 110, a three-dimension (3D) model 112, a finite element analysis (FEA) module 114, and one or more databases 119.

[0035] The manufacturing device 105 may be any type of manufacturing device capable of constructing an object having a cellular structure. In some embodiments, the manufacturing device 105 is an additive manufacturing device such as a 3D printer and may construct the object via one or more of binder jetting, directed energy deposition, material extrusion, powder bed fusion, sheet lamination, VAT polymerization, and material jetting. The manufacturing device 105 may be configured to manufacture the specimen 103, the component 102, or portions thereof.

[0036] The imaging device 106 is configured to scan the specimen 103 or a portion thereof to reconstruct a three-dimensional (3D) image of the target object, including the internal structure (e.g., the cellular structure) of the target object. It is also contemplated that the imaging device 106 may scan the component 102 or portions thereof. In some approaches, the imaging device 106 may scan a subset of cells 104 within the cellular structure of the component 102 or the specimen 103. In some aspects, the imaging device 106 may acquire image data without destroying the specimen 103. In this manner, the imaging device 106 may be employed to provide 3D images of a real cell geometry in the cellular structure of the specimen 103. In one example, the imaging device 106 may be a μ CT device that illuminates the specimen 103 using an x-ray source and acquire a series of two-dimensional (2D) images from different angles which are used to reconstruct a high-resolution 3D image of the specimen 103.

[0037] The imaging device 106 may be any suitable three-dimensional imaging device or scanner including, for

example, an in-situ tomography scanner such as an x-ray micro computed tomography (μ CT) scanner, a synchrotron tomography scanner, or other optical scanners. The imaging device **106** may image the specimen **103** with submicron resolution to reconstruct the shape or geometry of a cell in the cellular structure. In some embodiments, the imaging device **106** may be incorporated into or otherwise associated with the manufacturing device **105** or a corresponding manufacturing process.

[0038] A display device **108** may be configured to present the 3D image of the specimen **103** as generated by the imaging device **106**. The display device **108** may be associated with the imaging device **106**. The display device **108** may be of any suitable type including but not limited to, a cathode ray tube (CRT) device, a liquid crystal display (LCD) device, a light emitting diode (LED) device, etc. The display device **108** may also present additional information or attributes associated with the specimen **103** and/or an identifier in the image such as, for example, a name, model number, type, production date, etc. associated with the specimen **103**.

[0039] The user input device **110** is configured to receive input from a user. The input for a user may include, but is not limited to, device settings, user preferences, component information, etc. The user input device **110** can take any suitable form. For example, the user input device **110** may include, but is not limited to a mouse, a touchscreen, a keyboard, a trackpad, a number pad, etc.

[0040] In some embodiments, the display device **108** and the user input device **110** may be integrated into a single component, such as a touchscreen device. In some embodiments, the display device **108** and/or the user input device **110** may be included in a computing device such as, for example, a desktop computer, a laptop computer, a tablet, a mobile device, etc. One or both of the display device **108** and the user input device **110** may also be associated with the imaging device **106** and/or an electronic device that is integrated with or communicatively coupled with the imaging device **106**.

[0041] The 3D model **112** is a 3D model of the specimen **103**, the component **102**, or portions thereof, including any cellular structures therein. The 3D model **112** is stored in one or more of the databases **119**. Though, it is contemplated that the 3D model **112** need not be stored in the databases **119** and, in other configurations, may be stored or housed in another components or portion of the system **100**, such as in the FEA module **114** or the component analysis module **116** or may be received from a database or similar that is external to the system **100**. The 3D model **112** may be, for example, a model of the specimen **103** or the component **102** as-designed. The 3D model **112** depicts the geometry of the specimen **103** or of the component **102**. Equations, clouds of points, or other suitable approaches may reconstruct the 3D model **112** using image data or scans of the specimen **103** and/or the component **102** that are obtained using the imaging device **106**. The 3D model **112** may provide the actual cell geometry of the specimen **103** based on image data acquired by the imaging device **106**. Simulations may be performed on the 3D model **112** to evaluate performance and optimize the design of the component **102**. The 3D model **112** may be any suitable type of 3D model such as, for example, a computer-aided design (CAD) and/or computer-aided engineering (CAE) model. In some approaches, the 3D model **112** is an implicit model.

[0042] In some embodiments, data from the 3D model **112** may be exported or otherwise transmitted for input into the FEA module **114**. For example, as the FEA module **114** may receive a finite element mesh of the specimen **103** from the 3D model. Such a finite element mesh may include a plurality of nodes which help to define the structure of the specimen **103**.

[0043] The FEA module **114** is configured to perform finite element analysis for structural analysis of the specimen **103**, the component **102** or portions thereof, such as for a cell or for subset of cells **104** of the component **102**. Though the FEA module **114** is illustrated as being distinct from the control unit **118**, it is contemplated that, in some configurations, the FEA module **114** may be integrated into the control unit **118**. For example, the processor **120** may be configured to perform one or more of the functions of the FEA module **114**. For example, the FEA module **114** may be configured to employ calculations based on mathematical representations, models, and simulations of the specimen **103**, the component **102** or portions thereof to analyze how the component **102** behaves under various physical conditions, for example, subjected various stresses. In this manner, the FEA module **114** may be employed to determine the fatigue strength of the specimen **103**, the component **102** or portions thereof either as-designed (e.g., based on model data from the 3D model **112**) or as-manufactured (e.g., based on image data acquired from the imaging device **106**).

[0044] The FEA module **114** may also be configured to receive data indicative of mechanical properties, the geometry (e.g., data on the cellular structure of the component **102**), and/or data on the type of component **102** and/or specimen **103**. It is contemplated that the FEA module **114** may receive and utilize model data from the 3D model **112**, image data from the imaging device **106**, and/or data from one or more databases **119** as input data.

[0045] The FEA module **114** may be configured to generate the fatigue strength or other mechanical properties of the specimen **103**. The FEA module **114** may perform finite element analysis using the image data for the specimen **103** that is acquired by the imaging device **106**. The FEA module **114** may derive constants that are indicative of the mechanical properties, such as the fatigue strength, of the specimen **103**. The constants may include for example the constants indicative of stiffness, such as Young's modulus, Poisson's ratio, and tangent modulus. The constants may also include, for example, constants indicative of static stress, such as yield stress and ultimate tensile stress. The FEA module **114** may also perform finite element analysis using one or more periodic boundary conditions in order to simulate the component **102** in its entirety (or portions thereof) by modelling a finite representative volume element which, in this case, may be the specimen **103** that is scanned by the imaging device **106**.

[0046] In some embodiments, the FEA module **114** may be configured to identify local stresses, for the specimen **103** and/or for a unit cell thereof. The FEA module **114** may also be configured to identify local stresses on the component **102**.

[0047] In some aspects, the FEA module **114** may be homogenized for properties such as stiffness. In addition, the FEA module **114** may be homogenized for strength. The FEA module **114**, once homogenized, may not include cells of the cellular structure but, instead, represent a bulk material without cells. Homogenization may be performed in the

FEA module **114** to model the component **102** based on the properties and/or constants (e.g., stiffness) for the specimen **103**. For example, the stiffness for the specimen **103**, may be used to determine macroscale structural performance of the component **102**. Homogenization may result in a homogenized model of the component **102** without spatially dependent properties and/or constants. Thus, the properties of the specimen **103** (e.g., the microstructure) are applied to an entire volume of the component **102** (e.g., the macrostructure) or to any number of cells **104** in a volume of the component **102**. In this manner, the properties of the real cell geometry, which is present in the specimen **103**, may be applied to the full volume (or a larger volume) of the component **102**. The homogenized material may then be analyzed via the FEA module **114** (and/or an FEA solver, for example, the FEA module **114** may be an input to the FEA solver) to obtain the homogenized stresses for the component **102**.

[0048] The component evaluation module **116** may utilize statistical tools to represent the variability of the fatigue strength for the specimen **103** (e.g., in a given volume of the component **102** composed of a subset or finite number of cells **104**). Though the component evaluation module **116** is illustrated as being distinct from the control unit **118**, it is contemplated that, in some configurations, the component evaluation module **116** may be integrated into the control unit **118**. For example, the processor **120** may be configured to perform one or more of the functions of the component evaluation module **116**. The component evaluation module **116** may be configured to employ various statistical tools such as weakest-link scaling and statistics of extremes. The component evaluation module **116** may apply a weakest link model to estimate the behavior of a number of cells based on stresses at the failure area of the specimen **103**. Using weakest-link scaling, the entire component fails if the link or unit cell with the lowest strength fails. Weakest-link scaling may use finite element analysis to provide the worst-case static and/or fatigue strength for a cellular structure. In one example, the failure area in the specimen **103** may be used to estimate the behavior of the component **102** (e.g., in its entirety) by applying statistics of extremes. Statistics of extremes provides deviations from a median of probability distributions. The component evaluation module **116** may apply statistics of extremes to obtain a description of a tail of a distribution describing the strength of a single cell or a subset of cells in the cellular structure. The distribution describing the strength of the specimen **103** may then be used to extrapolate a probability distribution for the component **102** (e.g., in its entirety or for a number of cells thereof). The component evaluation module **116** may be configured to perform one or more of the approaches described with reference to FIG. 7.

[0049] The system **100** may further include one or more databases **119** that house various types of data useful to fatigue strength assessment. In some embodiments, the databases **119** may include image data of the specimen **103**, for example, image data acquired from the imaging device **106**. The databases **119** may also include data on or from the 3D model **112**, such as data to reconstruct the 3D geometry of the specimen or the component **102**.

[0050] The control unit **118** may function as a computing device to perform the functions and methods described herein. It is contemplated that the control unit **118** may include one or more of the 3D model **112**, the FEA module

114, and/or the component evaluation module **116** or otherwise may be in communication with these components of the system **100**. The control unit **118** may include one or more processors **120**, input/output (I/O) devices **122**, transceivers **124**, and memory devices **126**. The processors **120** may include any suitable processing device such as a microprocessor, microcontroller, integrated circuit, logic device, or other suitable processing device. The processors **120** may be used to execute or assist in executing the steps of the processes, methods, functionality and techniques described herein, and to control various communications, decisions, programs, content, listings, services, interfaces, logging, reporting, etc. Further, the one or more processors **120** may access the memory devices **126**, which may store instructions **130**, code and the like that are implemented by the processors **120** to implement intended functionality.

[0051] The memory devices **126** typically include one or more processor-readable and/or computer-readable media accessed by at least the processors **120** and may include volatile and/or nonvolatile media, such as RAM, ROM, EEPROM, flash memory and/or other memory technology. Further, the memory devices **126** are shown as internal to the control unit **118**; however, the memory devices **126** may be internal, external or a combination of internal and external memory. Similarly, some or all of the memory devices **126** can be internal, external or a combination of internal and external memory of the processors **120**. The memory devices **126** may be substantially any relevant memory such as, but not limited to, solid-state storage devices or drives, hard drive, one or more of universal serial bus (USB) stick or drive, flash memory secure digital (SD) card, other memory cards, and other such memory or combinations of two or more of such memory, and some or all of the memory may be distributed at multiple locations over a computer network. The memory devices **126** may store data **128** such as code, software, executables, scripts, data, content, lists, programming, programs, log or history data, engine information, component information, and the like. The various components of the system **100** may coupled together via a bus, or, in some configurations, the various components may actually be coupled to the control unit **118** and/or one or more other components directly.

[0052] Typically, the control unit **118** further includes one or more communication interfaces, ports, or transceivers **124** and the like allowing the control unit **118** to communicate over a communication bus, a distributed computer, and/or a communication network (e.g., a local area network (LAN), the Internet, wide area network (WAN), etc.) with other devices and/or other such communications or combinations of two or more such communication methods. Further, the transceivers **124** may be configured for wired, wireless, optical, fiber optical cable, satellite, or other such communication configurations or combinations of two or more such communications.

[0053] The I/O devices **122** may be any relevant port or combinations of ports, such as but not limited to USB, Ethernet, or other such ports. The I/O devices **122** may be configured to allow wired and/or wireless communication coupling to external components. For example, the I/O devices **122** may provide wired communication and/or wireless communication (e.g., Wi-Fi, Bluetooth, cellular, RF, and/or other such wireless communication), and in some instances may include any suitable wired and/or wireless interfacing device, circuit and/or connecting device, such as

but not limited to one or more transmitters, receivers, transceivers, or combination of two or more of such devices.

[0054] The control unit **118** may receive data from various components of the system **100**. Further, the control unit **118** may transmit data to various components of the system **100**. For example, the control unit **118** may receive model data, which may include one or more design parameters, from the 3D model **112** and may transmit the model data to the manufacturing device **105** so that the manufacturing device can manufacture the component **102** in accordance with model data. The control unit **118** may also receive input data from the user input device **110** and provide instructions to the imaging device **106** and/or the manufacturing device based on such input data. The control unit **118** may further receive image data from the imaging device **106** and/or from the one or more databases **119**. The control circuit may transmit image data to the 3D model **112** and/or to the FEA module **114**.

[0055] As illustrated in FIG. 2, the various components of the system **100** may communicate directly or indirectly, such as over one or more distributed communication networks, such as a network **132**. For example, the network **132** may include LAN, WAN, Internet, cellular, Wi-Fi, and other such communication networks or combinations of two or more such networks.

[0056] In certain embodiments, the system **100** may also include one or more testing devices **133** that are configured to test the specimen **103** and/or the component **102** as-manufactured. The testing devices **133** may be any devices suitable to conduct mechanical testing, for example, compression, tension, bending, torsion, or fatigue testing. The testing devices **133** may include one or more fatigue testing machines such as a wheel disk-hub fatigue test machine, a dynamic fatigue testing machine, a rotary bending fatigue testing machine, a servo hydraulic fatigue testing machine, a zipper reciprocating fatigue testing machine, a spring fatigue testing machine, an axial fatigue testing machine, a torsional fatigue testing machine, a radial fatigue testing machine, a cyclic fatigue testing machine. The testing devices **133** may also include one or more universal testing machines (UTM) that are configured to determine a material's strength and deformation behavior under compressive (pressing) or tensile loads. Such UTMS may also be configured to perform bend tests, for example, to evaluate material ductility, bend strength, fracture strength, and resistance to fracture. The testing devices **133** may also include one or more torsion testing machines configured to simulate torsional movements of materials to determine the torque load of specimens made of different materials. The testing devices **133** may include a test stand to hold a specimen and a load cell that translates a magnitude of a measured force to an electrical signal that can be quantified. The test stand may be configured to hold the specimen during testing and, in some approaches, includes a top grip to engage a top portion of the specimen and a bottom grip to engage a bottom portion of the specimen. It is contemplated that different test stand configurations may be employed based on the size and shape of the specimen. The force gauge may collect measurements over the course of the test and may output peak/and or average force values which may be translated into material properties.

[0057] The testing devices **133** may be controlled by a testing control unit which may be in communication with, for example, the control unit **118**. The testing control unit

may respond to command signals to operate the testing devices **133**. Further, data acquired or generated by the testing devices **133** may be transmitted to the databases **119**, the finite element analysis module **114**, and/or the component analysis module **116**.

[0058] In operation, the system **100** may be used to assess the fatigue strength of the component **102** as-manufactured. Rather than manufacturing, acquiring images, and analyzing of the component **102** in its entirety, the system **100** may manufacture the specimen **103**, which is representative of the component **102** as-manufactured. Based on analysis of the specimen **103** as described herein, the component **102** may subsequently be manufactured and the properties, such as the fatigue strength, of the component **102** as-manufactured predicted.

[0059] The imaging device **106** acquires one or more images of the specimen **103**. In some approaches, the imaging device **106** may acquire images of a subset of cells **104** in the specimen **103**. The images acquired by the imaging device **106** are used by the FEA module **114** to determine a fatigue strength for the specimen **103** or of a cell or a number of cells in the specimen **103**. The fatigue strength is used by the component evaluation module **116** to evaluate the fatigue strength for the component **102** as-manufactured at a macroscale.

[0060] In some approaches, the testing devices **133** may be also employed to detect anomalies in the component **102** as-manufactured. Anomalies may include any feature that is present in the component **102** but that should not be present according to the design intent. Anomalies may include, for example, defects, geometrical inaccuracies, and process-dependent anomalies such as pores, cracks, lack of fusion, etc. in the component **102**. For example, the testing devices **133** may perform compression, tension, and/or fatigue testing on the component **102** as-manufactured to detect defects or to determine mechanical properties, such as the fatigue strength, of the component **102** as-manufactured. The results from such testing may be used to perform fractography to determine the relationship between the microstructure of the component **102** and crack initiation and propagation. In this manner, it may be possible to determine the root cause of cracks or fractures in the component **102**.

[0061] In other approaches, the testing devices **133** may measure the strength, for example the actual fatigue strength, of the component **102** as-manufactured. Thus, the testing devices **133** may be used to generate design curves for the component **102**. The design curves may include the material allowable values for mechanical properties of the component **102**. For example, the design curves may include the maximum stress over which the material is expected to yield or the fatigue failure as a function of the number of fatigue cycles. The measured strength may be compared to the predicted strength, for example to the predicted fatigue strength, generated by the FEA module **114**. In this manner in order to determine the error or uncertainty in the predicted fatigue strength.

[0062] Turning to FIG. 3, a flow diagram of exemplary approaches for assessing fatigue strength of a component having a cellular structure are provided. In some embodiments, the approaches may be performed using the system **100** or portions thereof.

[0063] In the approach **134**, the analytical cell strength the component may be evaluated. Analytical cell strength provides the strength of a unit cell in the cellular structure of the

component as-designed and, accordingly, is a theoretical value. A 3D analytical model **136** of the component may be generated. The 3D analytical model **136** model may provide the analytic cell geometry **138** of the component as-designed. Finite element analysis **140** may be performed on the analytic cell geometry in order to obtain the analytical cell strength **142**.

[0064] In the approach **135**, the real cell strength of the component may be evaluated. The real cell strength may be determined, for example, by analyzing a specimen that is representative of the component as manufactured. Real cell strength provides the strength of a unit cell in the cellular structure of the component as-manufactured. A manufacturing process **144**, such as an additive manufacturing process, is used to produce a real cell geometry **146** which is present in the component as-manufactured. Finite element analysis **148** may be performed on the real cell geometry **146** in order to obtain the real cell strength **150**. Statistics of extremes **152** may then be used to predict the expected component strength **154** based on the real cell strength **150**. One or more design criteria **156** for the component (or a component of the same type as the component as-manufactured) may be derived from the expected component strength **154**.

[0065] The analytical cell strength **142** may be compared to the real cell strength **150** in order to assess differences in strength caused by the manufacturing process **144**. For example, there may be defects or abnormalities associated with the manufacturing process **144** which may result in a real cell strength **150** being lower than the analytical cell strength **142**.

[0066] Further, testing **158** may be performed on the real cell geometry **146** and/or on the component as-manufactured. For example, testing **158** may be performed to evaluate a measured strength **162** of the as-manufactured component that includes the real cell geometry **146**. The measured strength **162** may then be compared to the expected component strength **154**. Such a comparison may be used to evaluate error or uncertainty associated with the finite element analysis **148**. Error and uncertainties may also be caused by the 3D imaging resolution, inaccuracies during testing, and/or analytical models for fatigue strength definition. It is also contemplated that testing **158** may be performed for defect recognition **160** and, accordingly, may be used to identify one or more defects such as cracks in the real cell geometry **146** or in the component as-manufactured.

[0067] With reference to FIG. 4, an exemplary method of predicting an expected fatigue strength for an as-manufactured component having a cellular structure, which may also be referred to herein as a target component, is provided. In a typical application setting many (but not necessarily all) of the steps illustrated in FIG. 4 are carried out by a control circuit, such as the control unit **118**.

[0068] The method involves analyzing a specimen that is representative of the target component. It is contemplated that the control circuit may analyze one or more specimen. Increasing the number of specimen may increase the accuracy of the predicted fatigue strength. The specimen includes at least one cell of a cellular structure as-manufactured (e.g., a real cell geometry). In some approaches, the specimen may include a group of cells in the cellular structure of a component. In other approaches, the specimen may be a full component. The specimen may have cells of the same size, type, and/or geometry as the target component. In addition,

the specimen may be manufactured under conditions analogous to the manufacturing conditions of the target component.

[0069] In some aspects, the specimen may include about 2 to about 30 cells. In certain aspects, the specimen of the real cell geometry may be about 2 cells×2 cells×2 cells and, in other aspects, may be about 4 cells×4 cells×6 cells.

[0070] In FIG. 4, block **170** through block **174** illustrate the analysis of cells (or of a group of cells) in a cellular structure via a specimen of the cellular structure to obtain a fatigue strength for a cellular structure as a function of the number of cells in the cellular structure. Block **175** through block **177** illustrate a component level analysis that uses homogenization of a component to obtain a spatial distribution of stresses experienced by the component.

[0071] At block **170**, the control circuit receives image data for one or more specimen to reconstruct a plurality of 3D models of the specimen. In some approaches, the control circuit reconstructs a 3D model of each cell in the specimen. Though, it is contemplated that, in other approaches, the control circuit may reconstruct a 3D model for a number (less than all) of the cells in the specimen. For example, the control circuit may reconstruct 3D models of a group of cells in the specimen. Thus, the 3D models may be models of one or a plurality of cells. The plurality of 3D models is further analyzed at block **172** to block **174** to create a distribution of the fatigue strength of the specimen, which is described in further detail below. It is also contemplated that, in other embodiments, the 3D models may be analyzed to create a distribution of constants or properties that are indicative of fatigue strength (e.g., the fatigue stress concentration factor (K_f)). In some aspects, the control circuit may instruct one or more imaging devices to acquire images of the specimen. The control circuit may then receive the image data from the imaging device and use the image data to reconstruct the plurality of 3D models of the specimen. For example, the control circuit may be in communication with a such as a μ CT scanner and may instruct the scanner to acquire one or more images and then receive the images from the scanner to reconstruct the 3D models.

[0072] The image data may include, for example, one or more images of the cellular structure as-manufactured. It is also contemplated that the control circuit may directly or indirectly receive the 3D models of the one or more specimen, for example, from a database. The control circuit may receive the image data, either directly or indirectly, from an imaging device such as a μ CT scanner. In some approaches, the control circuit may receive the image data or the 3D models from a database housing such data. In some approaches, at block **170**, an imaging device may scan or acquire images of the one or more specimen in order to obtain the image data of the cellular structure as-manufactured. The image data may then be transmitted from the imaging device to the control circuit. In some aspects, the specimen may include about 2 to about 30 cells. In some aspects, the specimens of the real cell geometry may be about 2 cells×2 cells x 2 cells and, in other aspects, may be about 4 cells×4 cells×6 cells. In other aspects, the specimens may include a single cell (e.g., a single unit cell). It is to be understood that multiple specimens may be scanned and analyzed as described at block **172** to block **174** to create a distribution of the mechanical properties or constants indica-

tive thereof (e.g., the stress concentration factor (Kf), the fatigue limit (σ_{lim})), which is described in further detail below.

[0073] Turning briefly to FIG. 5, in one non-limiting example, the control circuit may analyze about 1 to M single cell models **182** of a cellular structure of the specimen. The single cell model **182** is a 3D model of a single cell of a specimen and reflects the real or as-manufactured cell geometry. The control circuit may scan the specimen using a μ CT scanner and reconstruct the single cell model **182** using image data from the scan. In one example, where M=100, the specimen included 100 cells and the control circuit reconstructs a 3D model for each of the 100 cells. The cells of the specimen and the cells of the target component may be of the same type (e.g., TPMS).

[0074] Still with reference to FIG. 5, in another non-limiting example, the control circuit may analyze about one (1) to N 8-cell volume models **184** of cells of a cellular structure of the specimen. The 8-cell volume model **184**, includes a group of 8 cells of the cellular structure of the specimen. The 8-cell volume model **184** is a 3D model of a volume of 8 cells as-manufactured and, accordingly, captures the real cell geometry of the specimen. The control circuit may scan the specimen using a μ CT scanner and reconstruct the 8-cell volume model **184** using image data from the scan. In one example, where N=4, 4 8-cell volumes (e.g., 4 distinct 2 cell $\times$ 2 cell $\times$ 2 cell groups of cells) are modeled to generate 4 8-cell volume models **184**. The cells in the groups of cells and the cells of the target component may be of the same type (e.g., TPMS).

[0075] Returning to FIG. 4, at block **172**, the control circuit determines local stresses for each of the plurality of 3D models reconstructed at block **170** for a given applied homogenized stress. The control circuit determines local stresses for the 3D models via finite element analysis with periodic boundary conditions. It is contemplated that control circuit may determine any composition of stress tensors for the nodes of the model of the specimen (e.g., the real cell geometry). For example, the control circuit may analyze a single node or any function of the tensors of the nodes around it. In some embodiments, the control circuit may also determine strains for the specimen. The control circuit may further determine one or more constants for the specimen, such as material-related parameters like El-Haddad's size parameter.

[0076] In some approaches, the control circuit may include or be in communication with an FEA module. The FEA module may determine applied homogenized stresses, strains, or other constants for the 3D models. The control circuit may perform simulations using the FEA module to simulate stresses on the 3D model. The FEA module may be used to simulate testing on 3D models of the specimen (e.g., on the real cell geometry) to derive the constants that define the behavior of the cellular structure when subjected to stresses. The FEA module uses periodic boundary conditions to evaluate the strength of a larger volume of the component as-manufactured based on the 3D modeled real cell geometry.

[0077] In some approaches, the control circuit determines the fatigue strength for a failure area of the 3D model (e.g., the failure area in cell or the failure area the group of cells modeled via the 3D model). For example, the fatigue limit (σ_{lim}) for the 3D model might be determined as the applied

stress, which causes the maximum local stress to be equal to the fatigue strength of the constitutive material.

[0078] At block **173**, the control circuit determines the fatigue strength for each of the plurality of 3D models for the given applied homogenized stress. Using the fatigue strength for various applied homogenized stresses, the control circuit generates a probability distribution function of the given 3D volume of cells present in the 3D model. For example, if the 3D models include a single cell, the control circuit generates a probability distribution function that provides the probability that a single cell of the specimen has a particular fatigue strength. In another example, if the 3D models include eight (8) cells, the control circuit generates a probability distribution function that provides the probability that an 8-cell volume of the specimen has a particular fatigue strength. Exemplary probability distribution functions of fatigue strength are depicted in FIG. 7 (see lines **202** for a single cell probability distribution function; see line **206** for an 8-cell probability distribution function).

[0079] The control circuit generates the probability distribution function, for example, for a single cell using the fatigue strength determined for each 3D model at block **173**. In particular, the control circuit generates a distribution of the fatigue strength for the 3D models and obtains a best fit of the distribution to create the probability distribution function. Referring again to FIG. 7, the control circuit may generate a distribution such as the distribution of fatigue strength shown by line **200** using the fatigue strengths determined via FEA simulations of a plurality of single cell models.

[0080] At block **174**, the control circuit predicts an expected fatigue strength for a volume comprising a number of cells (e.g., for the number of cells in the target component) by applying statistics of extremes to the probability distribution function generated at block **173**. The control circuit may employ statistics of extremes to extrapolate the fatigue strength of any number of cells (e.g., a target number of cells) in a component as-manufactured based on the probability distribution function of the fatigue strength for the 3D models. Thus, using statistics of extremes, it is possible to determine the fatigue strength for a cellular structure as a function of the number of cells (Ncells) in the cellular structure. FIG. 8 provides an exemplary graph that may be generated using statistics of extremes by the approach described at block **174**. In particular, line **234** in FIG. 8 provides fatigue limit for a component as a function of the number of cells (Ncells).

[0081] FIG. 7 illustrates an exemplary application of statistics of extremes to a probability distribution function. In FIG. 7, statistics of extremes is applied to the single cell probability distribution function (line **202**) to derive the probability distribution function for a target component comprising 360 cells (line **210**). Thus, the probability distribution function for the 3D models (which may include, for example, a single cell or a group of cells such as an 8-cell volume) is used to extrapolate the fatigue strength to larger volumes of the cellular structure (e.g., to a larger number of cells or a full component).

[0082] By some approaches, the following formula may be used to extrapolate the fatigue strength of a component as-manufactured based on the fatigue strength of the specimens as determined from 3D models of the specimens, where the 3D model may have 1 or more cells:

$$F_T = F_N^{(T/N)}$$

[0083] wherein

[0084] T is a target number of cells to be analyzed for a component as-manufactured;

[0085] F_T is a cumulative distribution function of fatigue strength for T cells in the component as-manufactured;

[0086] N is the number of cells in the 3D model, wherein N can be 1 or larger; and

[0087] F_N is a cumulative distribution function of fatigue strength for N cells.

[0088] A cumulative distribution function may refer to a real-valued random variable X or a distribution function of X , evaluated at x , that provides the probability that X will take a value less than or equal to x .

[0089] Using statistics of extremes, for example, applying the above formula, the control circuit may predict an expected fatigue strength for any volume comprising a number of cells. In one example, the control circuit predicts an expected fatigue strength for any number of cells in a cellular structure. Because the probability distribution function is generated based on 3D models of a real cell geometry, the expected fatigue strength captures effects present in the real cell geometry to improve accuracy of the expected fatigue strength. Statistics of extremes may predict expected fatigue strength for any number of cells have the same type of cellular structure as the specimen (e.g., the real cell geometry captured in the 3D models).

[0090] At block 175, the control circuit identifies the properties of an equivalent homogenous material representative of the cellular structure of the specimen via homogenization. For example, the control circuit may identify the elastic tensor or any elastic properties that is representative of the cellular structure of the specimen (and, accordingly, is also representative of the cellular structure of the target component). It may be desirable, for example, to simulate a component composed of a bulk material as opposed to simulating a component composed of a cellular structure, which may be computationally burdensome due the large number of cells in a component. By obtaining properties of an equivalent homogenous material that is representative of the cellular structure of the specimen (and of the target component) as described at block 175, it is possible to instead model the target component as a bulk material while still capturing the effects or properties of the cellular structure of the target component.

[0091] At block 176, the control circuit performs a component-level analysis of stresses of the target component. In the component-level analysis, the cellular structure of the target component is substituted with the equivalent homogenous material that was determined at block 175. In particular, the control circuit performs FEA analysis of the component, for example, via an FEA module. In the component-level analysis, the control circuit generates a component model that is homogenized or composed of a bulk material. The control circuit homogenizes the component model (e.g., an FEA module of the component) to represent the target component as a bulk material as opposed to as cellular structure. The properties of the equivalent homogenous material, which are representative of the properties of the cellular structure, are applied to the bulk material in the FEA module. In this manner, the bulk material of the modeled component is macroscopically equivalent to the cellular structure in the target component. The equivalent

homogenous material will exhibit equivalent macroscopic behavior to the microstructure (e.g., the cellular structure) of the target component.

[0092] At block 177, the control circuit discretizes the modeled component into subvolumes based on a spatial distribution of stresses in the modeled component. The stress spatial distribution provides stress on the modeled component as a function of the position within the modeled component. For example, the control circuit may filter or apply a mask the modeled component to select particular values or ranges of stress. In some approaches, the control circuit may filter or mask for the highest stresses on the component to identify failure areas of the modeled component. The control circuit may filter or apply or mask to the modeled component for a particular stress range to get the subvolumes of the modeled component that have a stress in the particular stress range.

[0093] For example, the control circuit may filter or apply a mask to the modeled component for stresses in the range of 90-100 MPa. The control circuit may then identify subvolumes within the modeled component that are subjected to stresses in the range of 90-100 MPa.

[0094] At block 178, the control circuit performs fatigue strength assessment for each subvolume (or some number of subvolumes) of the modeled component. The control circuit performs the fatigue strength assessment by comparing the stresses (from block 177) with the expected fatigue strength (from block 174) for the number of cells in the subvolume. The control circuit extrapolates the expected fatigue strength to a volume composed of the number of cells present in the subvolume.

[0095] For example, if a subvolume of 8 cells of the modeled component is subjected stresses in the range of 90-100 MPa, the control circuit uses the function (from block 174), which provides expected fatigue strength as a function of the number of cells in the cellular structure, to determine the expected fatigue strength for that subvolume. The control circuit then compares the expected fatigue strength for the subvolume to the stress on the subvolume as determined by the spatial distribution of stresses in the modeled component (from block 177) to assess whether the component would exceed the fatigue strength. In this manner, the control circuit may determine which subvolumes of the target component would fail first, which indicates the fatigue strength for the target component as a whole.

[0096] Based on the fatigue strength for the target component (or a portion or subvolume thereof), the control circuit may generate one or more design parameters for a component as-designed. The design parameters may be incorporated into the 3D analytical model to generate a blueprint or model of the component as-designed. Such a blueprint or model in the 3D analytical model may be used to manufacture the component as-designed. In one example, the design parameter may be a component geometry that maximizes or otherwise increases the fatigue strength of the component as-designed. In some embodiments, the fatigue strength may be used to build a margin into the design for a component.

[0097] The method may optionally include manufacturing or otherwise physically constructing the component as-designed according to the design parameter. In some approaches, the control circuit may output design data indicative of the design parameter. The control circuit may transmit design data to a manufacturing device, such as a 3D

printer. By one approach, this can comprise 3D printing the component as-designed in accordance with the design data derived in the method. It is also contemplated that the method may optionally include using the design parameter to physically construct the component as-designed.

[0098] In some approaches, the control circuit may generate one or more manufacturing parameters or parameters for a manufacturing device such as a 3D printer based on the expected fatigue strength of the component (or a portion or subvolume thereof). The manufacturing device may then manufacture the component as-designed according to the one or more manufacturing parameters in order to construct a physical component or part.

[0099] Turning to FIG. 6, an exemplary flow diagram illustrating analysis of a specimen **190** is shown. The analysis provides further detail on the analysis that is described with reference to block **170** to block **173** of FIG. 4 above. One or more specimens may be analyzed as shown in FIG. 6. The specimen **190** has a cellular structure and includes a plurality of cells.

[0100] An imaging device **192**, such as a μ CT scanner may acquire one or more images of the specimen **190**. The one or more images may be used to reconstruct multiple 3D models **194** of the specimen **190**. For example, the multiple 3D models **194** may be 3D models of each cell in the specimen **190**. In another example, the multiple 3D models **194** may be 3D models of a volume of cells in the specimen **190**. The 3D models may be finite element models of the specimen **190**.

[0101] At block **196**, a control circuit may then perform FEA analysis of the multiple 3D models **194** with period boundary conditions. It is contemplated that the FEA module may employ any other possible boundary conditions to mimic the homogenous material. The inputs to the FEA module at block **196** are the multiple 3D models **194**, applied loads, and boundary conditions. The applied stress is applied in a homogenous way to the 3D models and, thus, it is a macroscopic applied stress. That is, a load is applied to the entire surface and/or volume of the 3D model versus to portions thereof. The outputs generated by the FEA module at block **196** are maps of local stresses in each of the multiple 3D models **194**. The FEA module may simulate or apply various applied stresses to each (or some number) of the multiple 3D models **194** to generate the maps of local stresses.

[0102] At block **198**, a control circuit may determine the homogenized fatigue strength for each (or some) of the multiple 3D models **194** based on the maps of local stresses generated at block **196**. The most failure area in each 3D model reaches the fatigue strength for the 3D model. To obtain the homogenized fatigue strength, the control circuit applies a magnification to the local stress. The analysis is linear such that, if double applied stress doubles, the local stress doubles. The control circuit then determines the failure area of the 3D model that reaches the fatigue strength of the material of the specimen **190** (e.g., if the specimen **190** material such as an aluminum alloy the fatigue strength of the aluminum alloy would determine the failure area). The fatigue strength of the failure area would give the homogenized fatigue strength.

[0103] The procedure described at blocks **196** and **198** can be applied to any possible homogenized stress state.

[0104] At block **199**, the control circuit generates a probability distribution function of fatigue strength for the mul-

tiply 3D models **194** using the results from the analysis of each of the multiple 3D models **194**. Example results from such an analysis are presented, for example, in FIG. 7 at lines **200** and **202**.

[0105] The control circuit may then utilize the probability distribution function to determine an expected fatigue strength for a component or a portion of subvolume thereof. The control circuit may generate one or more manufacturing parameters or parameters for a manufacturing device such as a 3D printer based on the expected fatigue strength of the component (or a portion or subvolume thereof). The manufacturing device may then manufacture the component as-designed according to the one or more manufacturing parameters in order to construct a physical component or part.

[0106] FIGS. 7-8 provide an exemplary analysis of specimens to determine an expected fatigue strength for an as-manufactured component having a cellular structure. The analysis depicted in FIGS. 7-8 was performed using the single cell model **182**, the 8-cell volume model **184**, and the experimental specimen **186** depicted in FIG. 5.

[0107] FIG. 7 depicts Weibull probability plots of the fatigue limit (σ_{lim}) based on single cell specimens (e.g., the single cell model **182**), volume specimens (e.g., the 8-cell volume model **184**), and the experimental specimen **186**. The fatigue limit (σ_{lim}) measures the limit stress at which failure occurs for an infinite number of fatigue cycles.

[0108] Line **200** depicts simulation data for the fatigue limit (σ_{lim}). The simulation data in line **200** is derived from FEA simulations on the single cell models (**1** . . . **M**). The circular data points of line **200** each represent the simulation results from a distinct single cell model (e.g., results from each specimen-FEA simulation of the single cell model **2**, the single cell model **3**, etc. through the single cell model **M**). In particular, each circular data point represents the lowest fatigue limit (σ_{lim}) value in the single cell model as determined via FEA simulation. For example, the lowest fatigue limit (σ_{lim}) in the single cell model **182** is at failure area **182a**. Failure areas for each single cell model (**1** . . . **M**) are determined and the fatigue limit at the failure areas used to construct line **200**. The lowest fatigue limit (σ_{lim}) value is the fatigue limit (σ_{lim}) at the failure areas in the single cell model. Each distinct single cell model is obtained by manufacturing and acquiring images of a single cell to construct a 3D model of the real cell geometry. The 3D model of the real cell geometry is then analyzed using FEA simulation to estimate the fatigue limit of the single cell for each specimen, or at least some of the specimens. Thus, the simulation data in line **200** provides the cell-to-cell variability of the fatigue limit (σ_{lim}).

[0109] Line **202** provides a probability distribution of the fatigue limit (σ_{lim}) for a single cell. Line **202** is fitted to the single cell simulation data of line **200**. That is, line **202** is the best fit of the data in line **200**.

[0110] Line **204** depicts simulation data for the fatigue limit (σ_{lim}). The simulation data in line **200** is derived from FEA simulations on the 8-cell volume models (**1** . . . **N**). The square data points of line **204** each represent the simulation results from a distinct 8-cell volume model (e.g., results from FEA simulation of each specimen-8-cell model **2**, the 8-cell model **3**, etc. through the 8-cell model **N**). In particular, each square data point represents the lowest fatigue limit (σ_{lim}) value in the 8-cell volume model as determined via FEA simulation. The lowest fatigue limit (σ_{lim}) value is the

fatigue limit (σ_{lim}) at the failure area in the 8-cell volume model. For example, the lowest fatigue limit (σ_{lim}) in the 8-cell volume model **184** is at failure area **184a**. Failure areas for each 8-cell volume mode (**1** . . . **N**) would be determined and the fatigue limit at the failure areas used to construct line **204**. Each distinct 8-cell volume model is obtained by manufacturing and acquiring images of an 8-cell volume to construct a 3D model of the real cell geometry. The 3D model of the real cell geometry is then analyzed using FEA simulation to estimate the fatigue limit (σ_{lim}) of the 8-cell volume for each specimen, or at least some of the specimens.

[0111] Line **206** provides statistical estimations of the fatigue limit (σ_{lim}) for the 8-cell volume based on statistics of extremes. Line **206** was obtained using the following formula: $F_8 = F_1^8$, where F_1 is the function represented by line **202**. Thus, line **204** provides a distribution of fatigue limit (σ_{lim}) obtained by simulation while line **206** provides a distribution of fatigue limit (σ_{lim}) for the 8-cell volume obtained numerically. A comparison of line **204** with line **206** illustrates that the predicted fatigue limit (σ_{lim}) of the 8-cell volume using statistics of extremes is well aligned with the fatigue limit (σ_{lim}) data is derived from FEA simulations of 8-cell volume model, which captures the real cell geometry. Thus, the extrapolation performed using statistics of extremes is validated by simulations of the real cell geometry.

[0112] Line **208** depicts the experimental distribution of fatigue limit (σ_{lim}) for the experimental specimen **186**. The data for line **208** is obtained by subjecting the experimental specimen **186** to fatigue testing. Any suitable fatigue testing device may be used to perform fatigue testing.

[0113] Line **210** provides estimates of the fatigue limit (σ_{lim}) for the experimental specimen **186** of 360 cells based on statistics of extremes using the following formula: $F_{360} = F_1^{360}$, where F_1 is the function represented by line **202**. Thus, line **208** provide a distribution of fatigue limit (σ_{lim}) obtained experimentally while line **210** provides a distribution of fatigue limit (σ_{lim}) obtained numerically using statistics of extremes. A comparison of line **208** with line **210** illustrates that the predicted fatigue limit (σ_{lim}) of the experimental specimen **186** using statistics of extremes is well aligned with the fatigue limit (σ_{lim}) data is derived from fatigue testing of the experimental specimen **186**, which captures the real cell geometry. Thus, the extrapolation performed using statistics of extremes is validated by experimental data.

[0114] FIG. **8** depicts a graph of fatigue strength as a function of the number of cells in a component. The graph illustrates the effect of the real cell geometry as compared to the analytical cell geometry (e.g., the cell geometry as-designed). Line **230** provides the fatigue strength of the bulk material, that is, with no stress concentration. Line **232** provides the fatigue strength of the cells as-designed. Line **234** provides the fatigue strength of cells as-manufactured (e.g., as-built). Further, line **234** includes confidence bands, illustrating the 95% confidence interval, for the fatigue strength of cells as-manufactured. The fatigue strength values of line **234** were determined using the methods described herein.

[0115] The fatigue strength of cells as-manufactured (line **234**) is lower than the fatigue strength of cells as-designed (line **232**). As discussed above, this is due to effects of the manufacturing process, such as deviations introduced via the

manufacturing process. Further, the fatigue strength of cells as-designed (line **232**) is lower than the fatigue strength of the bulk material (line **230**). This is due to the effects of the cell geometry on fatigue strength.

[0116] FIG. **9A** depicts an exemplary S-N diagram generated via the methods described herein. The fatigue stress will depend on the material and geometry of the cellular structure. Using an FEA module which has been homogenized, it is possible to obtain a number of cycles to failure (Ncycles) based on a number of cells (Ncells) in a cellular structure and based on the homogenized stress (S) on the component subvolume. Thus, the FEA module is of a modeled component has been homogenized with an equivalent homogenous material that is representative of the cellular structure. The FEA module may be used to generate the fatigue strength value for the modeled component as a function of the number of cycles to failure (Ncycles). The number of cycles to failure (Ncycles) may be generated as function of the number of cells in a component (Ncells) and applied stress (S) on the component:

$$N_{cycles} = f(N_{cells}, S)$$

[0117] The fatigue strength (which may be used to generate the S-N curve) is a function of the number of cells (Ncells). Accordingly, the S-N curve will vary based on the number of cells (Ncells) in the component, with the stresses in the S-N shifting lower as the number of cells (Ncells) in the component increases. Thus, a particular S-N curve may be employed to assess the fatigue strength of a target component based on the number of cells in the target component. Using the S-N curves of FIG. **9A**, it is possible to determine the number of cycles to failure for a component based on the S-N curve, knowing homogenized stress on the target component and the number of cells in the target component. The component life corresponds with the number of cycles to failure (Ncycles). Different regions of a component will have different homogenized stresses and, accordingly, have a different number of cycles to failure (Ncycles). A failure area of the component is the region having the lowest number of cycles to failure, as this is the region of the component that will be first to fail. In this manner, determining the weakest link of the component predicts failure of the component as a whole.

[0118] FIG. **9B** depicts a graph of fatigue stress as function of the number of the cells in the cellular structure. The curves in FIG. **9B** illustrate fatigue stress as a function of the number of cells in a component for various regions of the S-N curves illustrated in FIG. **9A**. For the finite life region, a number of cells of a cellular structure will tolerate lower stresses for a larger number of cycles (e.g., 300k cycles) and may tolerate higher stresses for a lower number of cycles (e.g., 30k) before failing. For the infinite life region, a number of cells of a cellular structure will tolerate an even lower stress for a very large number of cycles (e.g., the infinite life).

[0119] It is contemplated that the curves depicted in FIG. **9B** may be generated in a manner similar to that described for line **234** in FIG. **8**.

[0120] The systems and methods described herein may be employed to analyze cellular structures or other lattice structures manufactured, for example, via additive manufacturing. Due to the large number of cells in a component having a cellular structure, prior analytical methods of determining an expected fatigue strength for a target com-

ponent were computationally expensive in computing power and time. By employing finite element analysis with periodic boundary conditions, homogenization of a finite element analysis model, the methods described here may reduce the computational effort involved in analytical methods for determining expected fatigue strength for a target component. Further, the systems and methods described herein allow the fatigue strength for an entire target component to be predicted or determined based on the analysis of fatigue strength for a smaller number of cells (e.g., a single cell or a subvolume of cells) by employing statistical tools that extrapolate properties of the smaller number of cells to the entire target component.

[0121] Further aspects of the disclosure are provided by the subject matter of the following clauses:

[0122] A computer-implemented method comprising: receiving image data for a specimen from an imaging device, the specimen including a plurality of cells of cellular structure as-manufactured; reconstructing a plurality of three-dimensional models of the specimen using the image data, the plurality of three-dimensional models each including a given volume of the specimen; determining local stresses for at least one of the plurality of three-dimensional models for a given applied stress via finite element analysis with periodic boundary conditions; determining a fatigue strength for the at least one of the plurality of three-dimensional models based on the local stresses to generate a probability distribution function for the given volume of the specimen; predicting an expected fatigue strength for a volume comprising a number of cells of a cellular structure by applying statistics of extremes to the probability distribution function for the given volume of the specimen; and causing a manufacturing device to form a part based on the expected fatigue strength.

[0123] The computer-implemented method of any preceding clause, further comprising: identifying properties of an equivalent homogenous material representative of the cellular structure; performing an analysis of stress for a target component to generate a spatial distribution of stress on the target component, wherein a cellular structure of the target component is substituted with the equivalent homogenous material; discretizing the target component into a plurality of subvolumes based on the spatial distribution of stress; and performing a fatigue assessment for at least some of the plurality of subvolumes by comparing a stress on a subvolume with the expected fatigue strength for the number of cells in the subvolume.

[0124] The computer-implemented method of any preceding clause, further comprising: applying weakest link analysis to the plurality of subvolumes, wherein the weakest link analysis includes: determining a failure area in the target component based on the fatigue strength for the plurality of subvolumes and the stress on the plurality of subvolumes; and determining the fatigue strength for the target component based on the failure area.

[0125] The computer-implemented method of any preceding clause, wherein the analysis of stress for the target component is performed via a finite element analysis model of the target component that has been homogenized with the equivalent homogenous material.

[0126] The computer-implemented method of any preceding clause, wherein the properties are elastic properties.

[0127] The computer-implemented method of any preceding clause, wherein the fatigue strength is an infinite life fatigue strength.

[0128] The computer-implemented method of any preceding clause, wherein the cellular structure is a lattice structure.

[0129] The computer-implemented method of any preceding clause, further comprising: generating a design parameter for a component including the cellular structure based on the expected fatigue strength, wherein the manufacturing device forms the part based on the design parameter.

[0130] The computer-implemented method of any preceding clause, further comprising: scanning a specimen including a plurality of cells of a cellular structure using an imaging device to generate the image data, the imaging device configured to acquire images of the cellular structure.

[0131] The computer-implemented method of any preceding clause, wherein the specimen is manufactured via an additive manufacturing device, and wherein the imaging device is an x-ray micro computed tomography (μ CT) scanner.

[0132] The computer-implemented method of any preceding clause, further comprising: determining a number of cycles to failure for a target component based on the local stresses and a target number of cells in the target component.

[0133] The computer-implemented method of any preceding clause, wherein the image data is obtained from an x-ray micro computed tomography scanner that is configured to scan the specimen.

[0134] The computer-implemented method of any preceding clause, wherein the expected fatigue strength of the number of cells in the cellular structure is predicted via a formula as follows: $FT = FN (T/N)$ wherein T is the number of cells in the cellular structure, FT is a cumulative distribution function for the expected fatigue strength of the number of cells, N is a number of cells in each specimen, wherein N can be 1 or larger, and FN is the cumulative distribution function for the number of cells in each specimen.

[0135] A system for predicting fatigue strength, the system comprising: at least one imaging device; at least one processor in communication with the at least one imaging device; and a memory device, the memory device storing instructions that when executed by the at least one processor causes the at least one processor to perform operations, the at least one processor configured to: receive image data for a specimen, the specimen including a plurality of cells of cellular structure from the at least one imaging device; reconstruct a plurality of three-dimensional models of the specimen using the image data, the plurality of three-dimensional models each including a given volume of the specimen; determine local stresses for at least one of the plurality of three-dimensional models for a given applied stress via finite element analysis with periodic boundary conditions; determine a fatigue strength for the at least one of the plurality of three-dimensional models based on the local stresses to generate a probability distribution function for the given volume of the specimen; and predict an expected fatigue strength for a volume comprising a number of cells of a cellular structure by applying statistics of extremes to the probability distribution function for the given volume of the specimen.

[0136] The system of clause any preceding clause, wherein the at least one processor is further configured to:

identify properties of an equivalent homogenous material representative of the cellular structure; perform an analysis of stress for a target component to generate a spatial distribution of stress on the target component, wherein a structure of the target component is substituted with the equivalent homogenous material; discretize the target component into a plurality of subvolumes based on the spatial distribution of stress; and perform a fatigue assessment for at least some of the plurality of subvolumes by comparing a stress on a subvolume with the expected fatigue strength for the number of cells in the subvolume.

[0137] The system of any preceding clause, wherein the at least one processor is further configured to: generate a design parameter for a component including the cellular structure based on the expected fatigue strength; and manufacture, via at least one manufacturing device in communication with the at least one processor, the component as-designed according to the design parameter.

[0138] The system of any preceding clause, wherein the at least one processor is further configured to transmit at least one signal to a manufacturing device, wherein the at least one signal is indicative of instructions for manufacturing a component including the cellular structure, the instructions based on the expected fatigue strength of the number of cells in the cellular structure as-manufactured.

[0139] The system of any preceding clause, wherein the system further includes at least one testing device configured to acquire a measured fatigue strength of the specimen, and wherein the processor is further configured to compare the measured fatigue strength to the expected fatigue strength to determine an amount of error in the expected fatigue strength.

[0140] A computer-implemented method comprising: causing an imaging device to scan a specimen including a plurality of cells of a cellular structure, the scan generating image data for the specimen; reconstructing a plurality of three-dimensional models of the specimen, the plurality of three-dimensional models each including a given volume of the specimen; determining local stresses for at least one of the plurality of three-dimensional models for a given applied stress via finite element analysis with periodic boundary conditions; determining a fatigue strength for the at least one of the plurality of three-dimensional models based on the local stresses to generate a probability distribution function for the given volume of the specimen; and predicting an expected fatigue strength for a volume comprising a number of cells of the cellular structure by applying statistics of extremes to the probability distribution function for the given volume of the specimen.

[0141] The computer-implemented method of any preceding clause, further comprising causing a manufacturing device to form a part based on the expected fatigue strength.

What is claimed is:

1. A computer-implemented method comprising:

receiving image data for a specimen from an imaging device, the specimen including a plurality of cells of cellular structure as-manufactured;

reconstructing a plurality of three-dimensional models of the specimen using the image data, the plurality of three-dimensional models each including a given volume of the specimen;

determining local stresses for at least one of the plurality of three-dimensional models for a given applied stress via finite element analysis with periodic boundary conditions;

determining a fatigue strength for the at least one of the plurality of three-dimensional models based on the local stresses to generate a probability distribution function for the given volume of the specimen;

predicting an expected fatigue strength for a volume comprising a number of cells of a cellular structure by applying statistics of extremes to the probability distribution function for the given volume of the specimen; and

causing a manufacturing device to form a part based on the expected fatigue strength.

2. The computer-implemented method of claim 1, further comprising:

identifying properties of an equivalent homogenous material representative of the cellular structure;

performing an analysis of stress for a target component to generate a spatial distribution of stress on the target component, wherein a structure of the target component is substituted with the equivalent homogenous material;

discretizing the target component into a plurality of subvolumes based on the spatial distribution of stress; and performing a fatigue assessment for at least some of the plurality of subvolumes by comparing a stress on a subvolume with the expected fatigue strength for the number of cells in the subvolume.

3. The computer-implemented method of claim 2, further comprising:

applying weakest link analysis to the plurality of subvolumes, wherein the weakest link analysis includes: determining a failure area in the target component based on the fatigue strength for the plurality of subvolumes and the stress on the plurality of subvolumes; and determining the fatigue strength for the target component based on the failure area.

4. The computer-implemented method of claim 2, wherein the analysis of stress for the target component is performed via a finite element analysis model of the target component that has been homogenized with the equivalent homogenous material.

5. The computer-implemented method of claim 2, wherein the properties are elastic properties.

6. The computer-implemented method of claim 1, wherein the fatigue strength is an infinite life fatigue strength.

7. The computer-implemented method of claim 1, wherein the cellular structure is a lattice structure.

8. The computer-implemented method of claim 1, further comprising:

generating a design parameter for a component including the cellular structure based on the expected fatigue strength, wherein the manufacturing device forms the part based on the design parameter.

9. The computer-implemented method of claim 1, further comprising:

scanning a specimen including a plurality of cells of a cellular structure using an imaging device to generate the image data, the imaging device configured to acquire images of the cellular structure.

10. The computer-implemented method of claim 1, wherein the specimen is manufactured via an additive manufacturing device, and wherein the imaging device is an x-ray micro computed tomography (μ CT) scanner.

11. The computer-implemented method of claim 1, further comprising:

determining a number of cycles to failure for a target component based on the local stresses and a target number of cells in the target component.

12. The computer-implemented method of claim 1, wherein the image data is obtained from an x-ray micro computed tomography scanner that is configured to scan the specimen.

13. The computer-implemented method of claim 1, wherein the expected fatigue strength of the number of cells in the cellular structure is predicted via a formula as follows:

$$F_T = F_N^{(T/N)}$$

wherein

T is the number of cells in the cellular structure,

F_T is a cumulative distribution function for the expected fatigue strength of the number of cells,

N is a number of cells in each specimen, wherein N can be 1 or larger, and

F_N is the cumulative distribution function for the number of cells in each specimen.

14. A system for predicting fatigue strength, the system comprising:

at least one imaging device;

at least one processor in communication with the at least one imaging device; and

a memory device, the memory device storing instructions that when executed by the at least one processor causes the at least one processor to perform operations, the at least one processor configured to:

receive image data for a specimen including a plurality of cells of cellular structure from the at least one imaging device;

reconstruct a plurality of three-dimensional models of the specimen using the image data, the plurality of three-dimensional models each including a given volume of the specimen;

determine local stresses for at least one of the plurality of three-dimensional models for a given applied stress via finite element analysis with periodic boundary conditions;

determine a fatigue strength for the at least one of the plurality of three-dimensional models based on the local stresses to generate a probability distribution function for the given volume of the specimen; and predict an expected fatigue strength for a volume comprising a number of cells of a cellular structure by applying statistics of extremes to the probability distribution function for the given volume of the specimen.

15. The system of claim 14, wherein the at least one processor is further configured to:

identify properties of an equivalent homogenous material representative of the cellular structure;

perform an analysis of stress for a target component to generate a spatial distribution of stress on the target component, wherein a structure of the target component is substituted with the equivalent homogenous material;

discretize the target component into a plurality of subvolumes based on the spatial distribution of stress; and perform a fatigue assessment for at least some of the plurality of subvolumes by comparing a stress on a subvolume with the expected fatigue strength for the number of cells in the subvolume.

16. The system of claim 14, wherein the at least one processor is further configured to:

generate a design parameter for a component including the cellular structure based on the expected fatigue strength; and

manufacture, via at least one manufacturing device in communication with the at least one processor, the component as-designed according to the design parameter.

17. The system of claim 14, wherein the at least one processor is further configured to transmit at least one signal to a manufacturing device, wherein the at least one signal is indicative of instructions for manufacturing a component including the cellular structure, the instructions based on the expected fatigue strength of the number of cells in the cellular structure.

18. The system of claim 14, wherein the system further includes at least one testing device configured to acquire a measured fatigue strength of the specimen, and wherein the at least one processor is further configured to compare the measured fatigue strength to the expected fatigue strength to determine an amount of error in the expected fatigue strength imaging.

19. A computer-implemented method comprising:

causing an imaging device in communication to scan a specimen including a plurality of cells of a cellular structure, the scan generating image data for the specimen;

reconstructing a plurality of three-dimensional models of the specimen, the plurality of three-dimensional models each including a given volume of the specimen;

determining local stresses for at least one of the plurality of three-dimensional models for a given applied stress via finite element analysis with periodic boundary conditions;

determining a fatigue strength for the at least one of the plurality of three-dimensional models based on the local stresses to generate a probability distribution function for the given volume of the specimen; and

predicting an expected fatigue strength for a volume comprising a number of cells of the cellular structure by applying statistics of extremes to the probability distribution function for the given volume of the specimen.

20. The computer-implemented method of claim 19, further comprising causing a manufacturing device to form a part based on the expected fatigue strength.

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