joined to the noodle along a second curved interface that starts at the second edge, and a composite laminate joined to the first flange by a first portion of an adhesive bondline, joined to the noodle by a second portion of the adhesive bondline, and joined to the second flange by a third portion of the adhesive bondline; (b) simulating propagation of ultrasonic waves that travel along the first portion of the adhesive bondline of the simulated curved composite laminate structure, separate at the first edge of the noodle of the simulated curved composite laminate structure, and then travel separately along the first interface and the second portion of the adhesive bondline of the simulated curved composite laminate structure; (c) storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents a simulated wave characteristic of simulated ultrasonic waves that have propagated through the simulated curved composite laminate structure from a first surface area of the composite laminate disposed adjacent to the first flange to a second surface area of the composite laminate disposed adjacent to the second flange; (d) generating ultrasonic waves which propagate through an actual curved composite laminate structure having a noodle, first and second bended sections and a composite laminate with material properties and a construction that is the same as material properties and a construction of the simulated curved composite laminate structure; (e) converting ultrasonic waves which have propagated through the actual curved composite laminate structure from a first surface area of the composite laminate disposed adjacent to a first flange of the first bended section to a second surface area of the composite laminate disposed adjacent to the second flange of the second bended section into measurement electrical signals; (f) processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic of actual ultrasonic waves that have propagated from the first surface area to the second surface area of the composite laminate of the actual curved composite laminate structure; (g) storing the measurement data in the non-transitory tangible computer-readable storage medium; (h) determining a difference between the empirical wave characteristic represented by the measurement data and the simulated wave characteristic represented by the reference data; and (i) classifying the

actual adhesive bondline; (g) storing the measurement data in the non-transitory tangible computer-readable storage medium; (h) determining a difference between the empirical wave characteristic represented by the measurement data and the simulated wave characteristic represented by the reference data; and (i) classifying the actual skin-stringer assembly as having an anomaly or not having an anomaly in dependence on the difference.

A further aspect is a method for structural health monitoring of a curved composite laminate structure comprising a noodle, the method comprising: (a) simulating an undamaged curved composite laminate structure including a noodle having straight and curved adhesive bondlines; (b) simulating propagation of an ultrasonic guided wave of a specified frequency which is guided through the undamaged structure and around the noodle by the straight and curved adhesive bondlines; (c) simulating respective damaged versions of the same structure having respective simulated defects of different types; (d) simulating propagation of an ultrasonic guided wave of the specified frequency which is guided through the damaged structure and around the noodle by the straight and curved adhesive bondlines; (e) storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents wave characteristics of simulated ultrasonic guided waves which have propagated through the damaged and undamaged structures and around the noodle and arrived at a sensing location on a surface of the simulated structure; (f) generating an ultrasonic guided wave of the specified frequency which propagates through an actual curved composite laminate structure including a noodle having straight and curved adhesive bondlines, wherein the actual curved composite laminate structure has material properties which are the same as or similar to material properties of the simulated curved composite laminate structure; (g) converting ultrasonic guided waves which have propagated through the actual curved composite laminate structure and around the noodle and arrived at a sensing location on a surface of the actual curved composite laminate structure into measurement electrical signals; (h) processing the measurement electrical signals to derive measurement data

representing an empirical wave characteristic; (i) storing measurement data representing the empirical wave characteristic in the non-transitory tangible computer-readable storage medium; (j) comparing the empirical wave characteristic represented by the measurement data to the simulated wave characteristics represented by the reference data; and (k) classifying the noodle area as being damaged or not in dependence on the results of comparing the measurement data to the reference data. If a determination is made that the noodle area is not damaged, then the actual curved composite laminate structure is neither repaired nor replaced. If a determination is made that the noodle area is damaged, then a flag is generated and thereafter the damaged actual curved composite laminate structure is either repaired or replaced.

Yet another aspect is a structural health monitoring system comprising: a wave generator, a pulser configured to send pulses to the wave generator, a wave sensor, a receiver configured to receive electrical signals from the wave sensor, and a computing system configured with simulation software, system control software for controlling the pulser and receiver, signal analysis software for analyzing signals output by the receiver, and a non-transitory tangible computer-readable storage medium. The simulation software is configured to enable the computing system to perform the following operations: simulating an undamaged curved composite laminate structure including a noodle having straight and curved adhesive bondlines; simulating propagation of an ultrasonic guided wave of a specified frequency which is guided through the undamaged structure and around the noodle by the straight and curved adhesive bondlines; simulating respective damaged versions of the same structure having respective simulated defects of different types; simulating propagation of an ultrasonic guided wave of the specified frequency which is guided through the damaged structure and around the noodle by the straight and curved adhesive bondlines; and storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents wave characteristics of simulated ultrasonic guided waves which have propagated through the damaged and undamaged structures and around the noodle and

arrived at a sensing location on a surface of the simulated structure. The system control software is configured to enable the computing system to perform the following operations: causing the wave generator to generate an ultrasonic guided wave of the specified frequency which propagates through an actual curved composite laminate structure including a noodle having straight and curved adhesive bondlines, wherein the actual curved composite laminate structure has material properties which are the same as or similar to material properties of the simulated curved composite laminate structure; and causing the wave sensor to convert ultrasonic guided waves which have propagated through the actual curved composite laminate structure and around the noodle and arrived at a sensing location on a surface of the actual curved composite laminate structure into measurement electrical signals. The signal analysis software is configured to enable the computing system to perform the following operations: processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic; and storing measurement data representing the empirical wave characteristic in the non-transitory tangible computer-readable storage medium. The system control software is further configured to enable the computing system to perform the following operations: comparing the empirical wave characteristic represented by the measurement data to the simulated wave characteristics represented by the reference data; and classifying the noodle area as being damaged or not in dependence on the results of comparing the measurement data to the reference data.

Other aspects of systems and methods for nondestructive inspection of a noodle area inside an adhesively bonded curved composite laminate structure are disclosed below.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, functions and advantages discussed in the preceding section may be achieved independently in various embodiments or may be combined in yet other embodiments. Various embodiments will be hereinafter described with reference to drawings for the purpose of illustrating

CLAIMS

1. A method for structural health monitoring of a curved composite laminate structure comprising a noodle, the method comprising:

simulating a curved composite laminate structure consisting of a noodle having first, second and third edges, a first bended section consisting of a first web, a first flange and a first radius connecting the first web to the first flange and joined to the noodle along a first curved interface that starts at the first edge, a second bended section consisting of a second web joined to the first web, a second flange and a second radius connecting the second web to the second flange and joined to the noodle along a second curved interface that starts at the second edge, and a composite laminate joined to the first flange by a first portion of an adhesive bondline, joined to the noodle by a second portion of the adhesive bondline, and joined to the second flange by a third portion of the adhesive bondline;

simulating propagation of ultrasonic waves that travel along the first portion of the adhesive bondline of the simulated curved composite laminate structure, separate at the first edge of the noodle of the simulated curved composite laminate structure, and then travel separately along the first interface and the second portion of the adhesive bondline of the simulated curved composite laminate structure;

storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents a simulated wave characteristic of simulated ultrasonic waves that have propagated through the simulated curved composite laminate structure from a first surface area of the composite laminate disposed adjacent to the first flange to a second surface area of the composite laminate disposed adjacent to the second flange;

generating ultrasonic waves which propagate through an actual curved composite laminate structure having a noodle, first and second bended sections and a composite laminate with material properties and a

construction that is the same as material properties and a construction of the simulated curved composite laminate structure;

converting ultrasonic waves which have propagated through the actual curved composite laminate structure from a first surface area of the composite laminate disposed adjacent to a first flange of the first bended section to a second surface area of the composite laminate disposed adjacent to the second flange of the second bended section into measurement electrical signals;

processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic of actual ultrasonic waves that have propagated from the first surface area to the second surface area of the composite laminate of the actual curved composite laminate structure;

storing the measurement data in the non-transitory tangible computer-readable storage medium;

determining a difference between the empirical wave characteristic represented by the measurement data and the simulated wave characteristic represented by the reference data; and

classifying the actual curved composite laminate structure as being anomalous or not anomalous in dependence on the difference.

2. The method as recited in claim 1, wherein a ratio of a radius of curvature of the first radius divided by a wavelength of the ultrasonic waves is approximately equal to 3.5.

3. The method as recited in claim 1, wherein the simulated curved composite laminate structure has no simulated defects, and classifying the actual curved composite laminate structure comprises classifying the actual curved composite laminate structure as being anomalous if the difference is greater than a specified threshold.

4. The method as recited in claim 1, wherein the simulated curved composite laminate structure has at least one simulated defect, and classifying the adhesive bondline comprises classifying the actual curved composite laminate structure as being anomalous if the difference is less than a specified threshold.

5. The method as recited in claim 1, wherein the noodle comprises unidirectional fiber-reinforced polymeric material.

6. The method as recited in claim 1, wherein each of the first and second interfaces has a hyperbolic profile.

7. The method as recited in claim 1, wherein the wave characteristic is time of travel of the ultrasonic waves as the ultrasonic waves propagate from the first surface area to the second surface area of the composite laminate of the actual curved composite laminate structure.

8. The method as recited in claim 7, further comprising estimating a size of an anomaly in the actual curved composite laminate structure based on a time of flight.

9. The method as recited in claim 1, wherein the wave characteristic is time of travel of the ultrasonic waves as the ultrasonic waves propagate from the first surface area of the composite laminate to the first edge of the noodle and then back to the first surface area of the composite laminate of the actual curved composite laminate structure.

10. The method as recited in claim 1, further comprising generating a flag in response to the actual curved composite laminate structure being classified as anomalous.

11. The method as recited in claim 10, further comprising repairing or replacing the actual curved composite laminate structure.

12. The method as recited in claim 1, wherein the composite laminate is a skin of a wing of an aircraft.

13. The method as recited in claim 1, wherein the first and second bended sections and the noodle are configured to form a blade stringer.

14. A method for structural health monitoring of a stringer-skin assembly, the method comprising:

simulating a stringer-skin assembly consisting of a noodle having a quasi-triangular profile, first and second bended sections having respective webs adhesively bonded together, and a skin adhesively bonded to the noodle and to respective flanges of the first and second bended sections along a simulated adhesive bondline;

simulating ultrasonic waves that propagate along the simulated adhesive bondline;

storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents a simulated wave characteristic of the simulated ultrasonic waves that propagate along the simulated adhesive bondline;

generating ultrasonic waves which propagate through an actual stringer-skin assembly consisting of a noodle, first and second bended sections and a composite laminate with material properties and a construction that is the same as material properties and a construction of the simulated stringer-skin assembly;

converting generated ultrasonic waves that have propagated along an actual adhesive bondline of the actual stringer-skin assembly into measurement electrical signals;

processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic of the generated ultrasonic waves that propagated along the actual adhesive bondline;

storing the measurement data in the non-transitory tangible computer-readable storage medium;

determining a difference between the empirical wave characteristic represented by the measurement data and the simulated wave characteristic represented by the reference data; and

classifying the actual skin-stringer assembly as having an anomaly or not having an anomaly in dependence on the difference.

15. The method as recited in claim 14, wherein the anomaly is a disbond along the actual adhesive bondline.

16. The method as recited in claim 14, wherein the anomaly is a delamination near the actual adhesive bondline.

17. The method as recited in claim 14, wherein a ratio of a radius of curvature of radius of the first bended section divided by a wavelength of the ultrasonic waves is approximately equal to 3.5.

18. The method as recited in claim 14, wherein the wave characteristic is time of travel of the generated ultrasonic waves as the generated ultrasonic waves propagate from a first surface area of the composite laminate adjacent to one edge of the actual adhesive bondline to a second surface area of the composite laminate adjacent to another edge of the actual adhesive bondline.

19. The method as recited in claim 18, further comprising estimating a size of an anomaly in the along or near the actual adhesive bondline based on a time of flight.

20. A method for structural health monitoring of a curved composite laminate structure comprising a noodle, the method comprising:

simulating an undamaged curved composite laminate structure including a noodle having straight and curved adhesive bondlines;

simulating propagation of an ultrasonic guided wave of a specified frequency which is guided through the undamaged structure and around the noodle by the straight and curved adhesive bondlines;

simulating respective damaged versions of the same structure having respective simulated defects of different types;

simulating propagation of an ultrasonic guided wave of the specified frequency which is guided through the damaged structure and around the noodle by the straight and curved adhesive bondlines;

storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents simulated wave characteristics of simulated ultrasonic guided waves which have propagated through the damaged and undamaged structures and around the noodle and arrived at a sensing location on a surface of the simulated structure;

generating an ultrasonic guided wave of the specified frequency which propagates through an actual curved composite laminate structure including a noodle having straight and curved adhesive bondlines, wherein the actual curved composite laminate structure has material properties which are the same as or similar to material properties of the simulated curved composite laminate structure;

converting ultrasonic guided waves which have propagated through the actual curved composite laminate structure and around the noodle and arrived at a sensing location on a surface of the actual curved composite laminate structure into measurement electrical signals;

processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic;

storing measurement data representing the empirical wave characteristic in the non-transitory tangible computer-readable storage medium;

comparing the empirical wave characteristic represented by the measurement data to the simulated wave characteristics represented by the reference data; and

classifying the noodle area as being damaged or not in dependence on the results of comparing the measurement data to the reference data.

21. The method as recited in claim 20, wherein if a determination is made that the noodle area is not damaged, then the actual curved composite laminate structure is neither repaired nor replaced.

22. The method as recited in claim 20, wherein if a determination is made that the noodle area is damaged, then a flag is generated and thereafter the damaged actual curved composite laminate structure is either repaired or replaced.

23. A structural health monitoring system comprising:

a wave generator, a pulser configured to send pulses to the wave generator, a wave sensor, a receiver configured to receive electrical signals from the wave sensor, and a computing system configured with simulation software, system control software for controlling the pulser and receiver, signal analysis software for analyzing signals output by the receiver, and a non-transitory tangible computer-readable storage medium;

wherein the simulation software is configured to enable the computing system to perform the following operations:

simulating an undamaged curved composite laminate structure including a noodle having straight and curved adhesive bondlines;

simulating propagation of an ultrasonic guided wave of a specified frequency which is guided through the undamaged structure and around the noodle by the straight and curved adhesive bondlines;

simulating respective damaged versions of the same structure having respective simulated defects of different types;

simulating propagation of an ultrasonic guided wave of the specified frequency which is guided through the damaged structure and around the noodle by the straight and curved adhesive bondlines; and

storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents wave characteristics of simulated ultrasonic guided waves which have propagated through the damaged and undamaged structures and around the noodle and arrived at a sensing location on a surface of the simulated structure;

wherein the system control software is configured to enable the computing system to perform the following operations:

causing the wave generator to generate an ultrasonic guided wave of the specified frequency which propagates through an actual curved composite laminate structure including a noodle having straight and curved adhesive bondlines, wherein the actual curved composite laminate structure has material properties which are the same as or similar to material properties of the simulated curved composite laminate structure; and

causing the wave sensor to convert ultrasonic guided waves which have propagated through the actual curved composite laminate structure and around the noodle and arrived at a sensing location on a surface of the actual curved composite laminate structure into measurement electrical signals;

wherein the signal analysis software is configured to enable the computing system to perform the following operations:

processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic; and

storing measurement data representing the empirical wave characteristic in the non-transitory tangible computer-readable storage medium; and

wherein the system control software is further configured to enable the computing system to perform the following operations:

comparing the empirical wave characteristic represented by the measurement data to the simulated wave characteristics represented by the reference data; and

classifying the noodle area as being damaged or not in dependence on the results of comparing the measurement data to the reference data.