interfaces of two materials. These characteristics result in the interface waves exhibiting high sensitivity to interfacial damages of hybrid structures at selected modes and frequencies, compared to other ultrasonic waveforms, which typically propagate through the thicknesses of the media.

One aspect of the subject matter disclosed in detail below is a method for structural health monitoring of an adhesive bondline in a structure, comprising: (a) simulating a structure comprising first and second simulated substrates joined along a simulated adhesive bondline; (b) simulating propagation of ultrasonic waves along a portion of the simulated adhesive bondline; (c) storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents a wave characteristic of simulated ultrasonic waves that have propagated along the portion of the simulated adhesive bondline and arrived at a sensing location on a surface of the simulated structure; (d) generating ultrasonic waves which propagate along a portion of an adhesive bondline that joins first and second substrates of an actual structure, wherein the first and second substrates and the adhesive bondline have material properties which are substantially the same as material properties of the first and second simulated substrates and simulated adhesive bondline respectively; (e) converting ultrasonic waves which have propagated along the portion of the adhesive bondline and arrived at a sensing location on a surface of the actual structure into measurement electrical signals; (f) processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic; (g) storing the measurement data representing the empirical wave characteristic in the non-transitory tangible computer-readable storage medium; (h) determining a difference between the measurement data and the reference data; (i) classifying the adhesive bondline as being damaged or not in dependence on the difference; (j) generating a flag in response to the adhesive bondline being classified as damaged; and (k) repairing or replacing the damaged adhesive bondline. In one example scenario, the first substrate is a metallic substrate and the second substrate is a composite laminate.

In accordance with one embodiment, the simulated adhesive bond has no simulated defects, and classifying the adhesive bondline comprises classifying the adhesive bondline as being damaged if the difference is greater than a specified threshold. In accordance with another embodiment, the simulated adhesive bond has at least one

simulated defect, and classifying the adhesive bondline comprises classifying the adhesive bondline as being damaged if the difference is less than a specified threshold.

The wave characteristics used to discriminate damage in the bondline may be one or more of the following parameters: time of travel, change in amplitude, change in phase, and change in wave energy distribution of the ultrasonic waves as the ultrasonic waves propagated along the portion of the adhesive bondline.

One advantage of combining numerical simulation with ultrasonic inspection is that a simulated setup that shows acceptable efficacy can be replicated for purposes of inspecting an actual structure. In particular, the generating location used to simulate inspection of the simulated structure and the generating location on the actual structure can be the same, and the sensing location used to simulate inspection of the simulated structure and the sensing location on the actual structure can be the same.

Another aspect of the subject matter disclosed in detail below is a method for structural health monitoring of an adhesive bondline, comprising: (a) simulating a structure comprising first and second simulated substrates joined along a simulated undamaged adhesive bondline free of defects; (b) simulating propagation of ultrasonic waves along a portion of the simulated undamaged adhesive bondline free of defects; (c) simulating respective structures comprising the first and second simulated substrates joined along respective simulated damaged adhesive bondlines having respective defects of different lengths, wherein the undamaged adhesive bondline and the damaged adhesive bondlines have the same material properties and the same thickness; (d) simulating propagation of ultrasonic waves along a portion of each simulated damaged adhesive bondline; (e) storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents wave characteristics of simulated ultrasonic waves that have propagated along the respective portions of the undamaged and simulated damaged adhesive bondlines and arrived at a sensing location on a surface of the simulated structure; (f) generating ultrasonic waves which propagate along a portion of an adhesive bondline that joins first and second substrates of an actual structure, wherein the first and second substrates and the adhesive bondline have material properties which are substantially the same as material properties of the first and second simulated substrates and simulated adhesive bondlines respectively; (g) converting ultrasonic waves which have propagated along the portion of the adhesive bondline and arrived at a sensing

location on a surface of the actual structure into measurement electrical signals; (h) processing the measurement electrical signals to derive measurement data representing an empirical wave characteristic; (i) storing the measurement data representing the empirical wave characteristic in the non-transitory tangible computer-readable storage medium; (j) comparing the measurement data to the reference data; (k) classifying the adhesive bondline as being damaged or not in dependence on the results of comparing the measurement data to the reference data. In example scenarios, the method may further include (l) generating a flag in response to the adhesive bondline being classified as damaged; and (m) repairing or replacing the damaged adhesive bondline.

A further aspect of the subject matter disclosed in detail below 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 a structure comprising first and second simulated substrates joined along a simulated undamaged adhesive bondline free of defects; simulating propagation of ultrasonic waves along a portion of the simulated undamaged adhesive bondline free of defects; simulating respective structures comprising the first and second simulated substrates joined along respective simulated damaged adhesive bondlines having respective defects of different lengths, wherein the undamaged adhesive bondline and the damaged adhesive bondlines have the same material properties and the same thickness; simulating propagation of ultrasonic waves along a portion of each simulated damaged adhesive bondline; and storing reference data in the non-transitory tangible computer-readable storage medium, which reference data represents wave characteristics of simulated ultrasonic waves that have propagated along the respective portions of the undamaged and simulated damaged adhesive bondlines 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 ultrasonic waves which propagate along a portion of an adhesive bondline that joins first and second substrates of an actual structure, wherein the first and second substrates and the adhesive

bondline have material properties which are the substantially same as material properties of the first and second simulated substrates and simulated adhesive bondlines respectively; and causing the wave sensor to convert ultrasonic waves which have propagated along the portion of the adhesive bondline and arrived at a sensing location on a surface of the actual 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 the 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 measurement data to the reference data; and classifying the adhesive bondline as being damaged or not in dependence on the results of comparing the measurement data to the reference data. In an example scenario, the system control software is further configured to enable the computing system to generate a flag in response to the adhesive bondline being classified as damaged. The empirical wave characteristic is selected from the following group: wave velocity, wavefront time of flight over a given distance, wave attenuation and wave energy dissipation.

Other aspects of methods for characterizing adhesively bonded joints in structures and predicting performance of adhesively bonded structures are disclosed below.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, functions and advantages discussed in the preceding section can 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 the above-described and other aspects.

FIG. 1 shows one embodiment of an adhesively bonded hybrid structure that can be simulated using the methods disclosed herein. In particular, the diagram shows an ultrasonic wave generator and an ultrasonic wave sensor placed on a surface of a composite laminate on opposite sides of an attached metallic substrate for the purpose of non-destructively inspecting the bondline.

FIG. 2 is a diagram representing an isometric view of a model (using the ABAQUS composite layup tool) of a composite section.

CLAIMS

1. A method for structural health monitoring of an adhesive bondline in an actual structure, the method comprising:

simulating a structure comprising first and second simulated substrates joined along a simulated adhesive bondline;

simulating propagation of ultrasonic waves along a portion of the simulated adhesive bondline;

storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents a wave characteristic of simulated ultrasonic waves that have propagated along the portion of the simulated adhesive bondline and arrived at a sensing location on a surface of the simulated structure;

generating ultrasonic waves which propagate along a portion of the adhesive bondline that joins first and second substrates of the actual structure, wherein the first and second substrates and the adhesive bondline have material properties which are substantially the same as material properties of the first and second simulated substrates and simulated adhesive bondline respectively;

converting ultrasonic waves which have propagated along the portion of the adhesive bondline and arrived at a sensing location on a surface of the actual structure into measurement electrical signals;

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

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

determining a difference between the measurement data and the reference data; and

classifying the adhesive bondline as being damaged or not in dependence on the difference.

2. The method as recited in claim 1, wherein the simulated adhesive bondline has no simulated defects, and classifying the adhesive bondline comprises classifying the adhesive bondline as being damaged if the difference is greater than a specified threshold.

3. The method as recited in claim 1, wherein the simulated adhesive bondline has at least one simulated defect, and classifying the adhesive bondline comprises classifying the adhesive bondline as being damaged if the difference is less than a specified threshold.

4. The method as recited in any one of claims 1 to 3, wherein the first substrate is a metallic substrate and the second substrate is a composite laminate.

5. The method as recited in any one of claims 1 to 4, wherein the wave characteristic is time of travel of the ultrasonic waves as the ultrasonic waves propagated along the portion of the adhesive bondline.

6. The method as recited in any one of claims 1 to 5, wherein the wave characteristic is change in amplitude of the ultrasonic waves as the ultrasonic waves propagated along the portion of the adhesive bondline.

7. The method as recited in any one of claims 1 to 6, wherein the wave characteristic is change in phase of the ultrasonic waves as the ultrasonic waves propagated along the portion of the adhesive bondline.

8. The method as recited in any one of claims 1 to 7, wherein the wave characteristic is change in wave energy distribution of the ultrasonic waves as the ultrasonic waves propagated along the portion of the adhesive bondline.

9. The method as recited in any one of claims 1 to 8, further comprising generating a flag in response to the adhesive bondline being classified as damaged.

10. The method as recited in claim 9, further comprising repairing or replacing the damaged adhesive bondline.

11. The method as recited in any one of claims 1 to 10, wherein the simulated adhesive bondline of the simulated structure and the adhesive bondline of the actual structure have the same thickness.

12. The method as recited in any one of claims 1 to 11, wherein the sensing location on the surface of the simulated structure and the sensing location on the surface of the actual structure are the same.

13. The method as recited in claim 12, further comprising:

simulating generation of ultrasonic waves at a generating location on the surface of the simulated structure; and

generating ultrasonic waves at a generating location on the surface of the actual structure,

wherein the generating location on the surface of the simulated structure and the generating location on the surface of the actual structure are the same.

14. A method for structural health monitoring of an adhesive bondline, the method comprising:

simulating a structure comprising first and second simulated substrates joined along a simulated undamaged adhesive bondline free of defects;

simulating propagation of ultrasonic waves along a portion of the simulated undamaged adhesive bondline free of defects;

simulating respective structures comprising the first and second simulated substrates joined along respective simulated damaged adhesive bondlines having respective defects of different lengths, wherein the undamaged adhesive bondline and the damaged adhesive bondlines have the same material properties and the same thickness;

simulating propagation of ultrasonic waves along a portion of each simulated damaged adhesive bondline;

storing reference data in a non-transitory tangible computer-readable storage medium, which reference data represents wave characteristics of simulated ultrasonic waves that have propagated along the respective portions of the undamaged and simulated damaged adhesive bondlines and arrived at a sensing location on a surface of the simulated structure;

generating ultrasonic waves which propagate along a portion of an adhesive bondline that joins first and second substrates of an actual structure, wherein the first and second substrates and the adhesive bondline have material properties which are substantially the same as material properties of the first and second simulated substrates and simulated adhesive bondlines respectively;

converting ultrasonic waves which have propagated along the portion of the adhesive bondline and arrived at a sensing location on a surface of the actual structure into measurement electrical signals;

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

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

comparing the measurement data to the reference data; and

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

15. The method as recited in claim 14, wherein the first substrate is a metallic substrate and the second substrate is a composite laminate.

16. The method as recited in claim 14 or 15, further comprising generating a flag in response to the adhesive bondline being classified as damaged.

17. The method as recited in claim 16, further comprising repairing or replacing the damaged adhesive bondline.

18. 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 a structure comprising first and second simulated substrates joined along a simulated undamaged adhesive bondline free of defects;

simulating propagation of ultrasonic waves along a portion of the simulated undamaged adhesive bondline free of defects;

simulating respective structures comprising the first and second simulated substrates joined along respective simulated damaged adhesive bondlines having respective defects of different lengths, wherein the undamaged adhesive bondline and the damaged adhesive bondlines have the same material properties and the same thickness;

simulating propagation of ultrasonic waves along a portion of each simulated damaged adhesive bondline; and

storing reference data in the non-transitory tangible computer-readable storage medium, which reference data represents wave characteristics of simulated ultrasonic waves that have propagated along the respective portions of the undamaged and simulated damaged adhesive bondlines 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 ultrasonic waves which propagate along a portion of an adhesive bondline that joins first and second substrates of an actual structure, wherein the first and second substrates and the adhesive bondline have material properties which are substantially the same as material properties of the first and second simulated substrates and simulated adhesive bondlines respectively; and

causing the wave sensor to convert ultrasonic waves which have propagated along the portion of the adhesive bondline and arrived at a sensing location on a surface of the actual 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 the 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 measurement data to the reference data; and

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

19. The system as recited in claim 18, wherein the system control software is further configured to enable the computing system to generate a flag in response to the adhesive bondline being classified as damaged.

20. The system as recited in claim 18 or 19, wherein the empirical wave characteristic is selected from the following group: wave velocity, wavefront time of flight over a given distance, wave attenuation, and wave energy dissipation.