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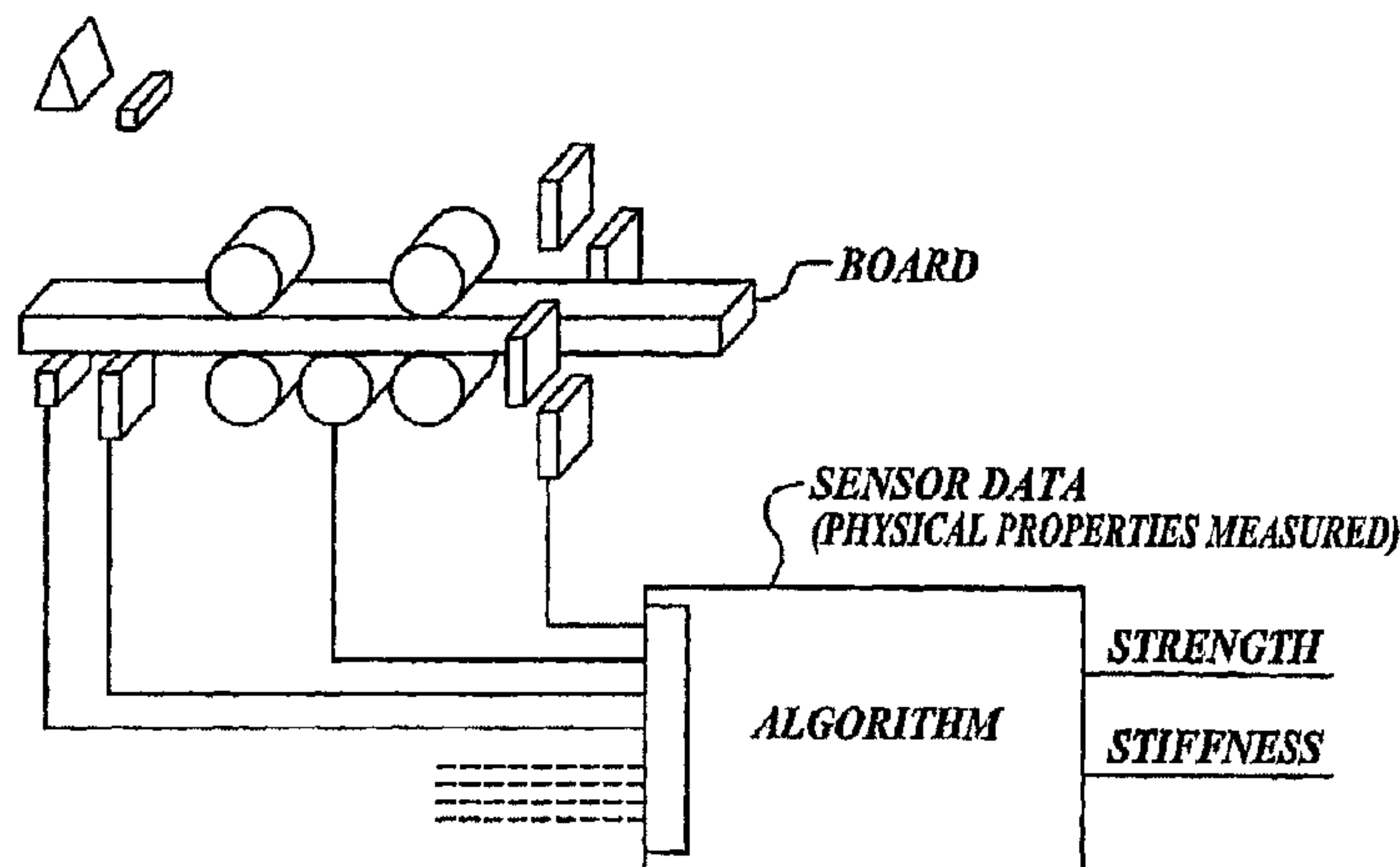
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(54) Titre : PROCEDE DE PREDICTION DE RESISTANCE ET DE RIGIDITE DE BOIS

(54) Title: METHOD OF WOOD STRENGTH AND STIFFNESS PREDICTION



(57) Abrégé/Abstract:

A method of non-destructive testing of a wood piece using a multiplicity of sensors. The method may include the steps of sensing the wood piece; collecting information from the sensors; and integrating the information into a physical model providing for strength and stiffness prediction. The collected information relate to material characteristics of the wood piece and to fiber quality characteristics of the wood piece. The material characteristics may include one or more of the following material characteristics of the wood piece: growth ring thickness; grain angle deviation; clear wood density; knot location; knot density; knot type; knot size; location in the tree from which the wood piece was cut. The fiber quality characteristics may include one or more of the following fiber quality characteristics: microfibril angle, juvenile wood, biodeterioration; reaction wood species; and manufacturing or drying defects including one or more of the following defects: sawcuts, checks, shake; size of actual cross-section, and species.

ABSTRACT

A method of non-destructive testing of a wood piece using a multiplicity of sensors. The method may include the steps of sensing the wood piece; collecting information from the sensors; and integrating the information into a physical model providing for strength and stiffness prediction. The collected information relate to material characteristics of the wood piece and to fiber quality characteristics of the wood piece. The material characteristics may include one or more of the following material characteristics of the wood piece: growth ring thickness; grain angle deviation; clear wood density; knot location; knot density; knot type; knot size; location in the tree from which the wood piece was cut. The fiber quality characteristics may include one or more of the following fiber quality characteristics: microfibril angle, juvenile wood, biodeterioration; reaction wood species; and manufacturing or drying defects including one or more of the following defects: sawcuts, checks, shake; size of actual cross-section, and species.

METHOD OF WOOD STRENGTH AND STIFFNESS PREDICTION

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Field of the Invention

The present invention relates generally to wood strength and stiffness prediction.

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Background of the Invention

It can be appreciated that wood strength grading has been in use for many years. This has traditionally been accomplished by using visual grading rules to predict strength. Other technologies such as mechanical bending and X-ray, to sense density, have been used to estimate the strength of wood.

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The main problem with conventional visual wood grading is that it does not predict strength or stiffness accurately. The use of the mechanical bending improved the ability to predict stiffness of the lumber but the correlation to strength is poor. X-ray based systems predict strength and stiffness based on density only.

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While these devices have been suitable for the particular purpose to which they addressed, they are not as suitable for highly accurate strength and stiffness prediction of today's variable and often low-quality wood resource.

Summary of the Invention

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The present invention provides a new prediction method of wood strength and stiffness.

The general purpose of the present invention, which will be described subsequently in greater detail, is to provide a new prediction method that has many of the advantages of the board strength prediction methods mentioned above and in addition, novel features that result in a greater prediction accuracy.

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To attain this, the present invention includes generally the use of streams of sensor information integrating into a physical model providing for strength and stiffness prediction. It is to be understood however that the invention is not limited in its application to the details of the method and to any arrangements of the components set forth in the following description or illustrated in the drawings, or to the details of the algorithm

employed. The invention is capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of the description and should not be regarded as limiting.

5 One object of the present invention is to provide a prediction of wood strength that will predict the strength and stiffness in the lumber based on a physical model using several sensing technologies. Physical model, in this context, refers generally to an algorithm that utilizes the material mechanical behavior and impact of various wood characteristics on strength and stiffness.

10 Another object is to provide a prediction of wood strength and stiffness that can integrate many technologies into a single model thereby providing differing accuracy prediction based on the sensors used.

 Another object is to provide a prediction of wood strength and stiffness that with sensor technologies added together improves the ability of any one sensor to predict
15 strength and stiffness.

 To the accomplishment of the above and related objects, this invention may be embodied in the form illustrated in the accompanying drawings, attention being called to the fact, however, that the drawings are illustrative only, and that changes may be made in the specific construction illustrated.

20 In one aspect, the method of the present invention may be characterized as a method of, and corresponding computer program means for accomplishing, non-destructive testing of a wood piece using a multiplicity of sensors. The method may include the steps of, and the program the computer readable program code means for causing the controlling and processing of, the following:

- 25 a) sensing the wood piece,
 b) collecting information from the sensors, and
 c) integrating the information into a physical model providing for strength and stiffness prediction.

 The step of collecting information may include collecting information relating to
30 material characteristics of the wood piece and relating to fiber quality characteristics of the wood piece. The material characteristics may include one or more of the following material characteristics of the wood piece: growth ring thickness; grain angle deviation; clear wood density; knot location; knot density; knot type; knot size; location in the tree

from which the wood piece was cut. The fiber quality characteristics may include one or more of the following fiber quality characteristics: microfibril angle, juvenile wood, biodeterioration; reaction wood species; and manufacturing or drying defects including one or more of the following defects: sawcuts, checks, shake; size of actual cross-section, and
5 species.

In one embodiment the method further includes the steps of providing one or more of the following sensor types: X-ray, microwave, camera vision, laser triangulation three-dimensional geometry, material vibration measurements, laser based tracheid effect measurement.

10 The method and software (alternatively referred to as a computer program product) for implementing same may also be characterized as including, respectively, the following steps or program code means for causing the implementation of the following steps:

- a) Measuring of the piece with a multiplicity of sensors;
- b) Estimating wood volume characteristics, including one or more of the
15 following: clear wood density, grain angle, moisture content, growth ring angle, location in the tree from which the wood was cut, fiber quality including microfibril angle, and three dimensional geometry of a scanned object;
- c) Detecting size, location and classification of wood defects, including one or more of the following: knots, biodeterioration, reaction wood, juvenile wood,
20 manufacturing and drying defects, pith, pitch, wet pockets;
- d) Subsequently inputting corresponding measured, estimated or detected information from the measuring, estimating or detecting steps into a physical model of the wood piece;
- e) Predicting strength and stiffness based on the effect of the estimated
25 information from the step of estimating the volume characteristics and the detected information from the step of detecting size, location and classification of wood defects on mechanical behavior of the wood piece.

The further step of constructing clear wood density equivalent as a first step in
30 strength and stiffness prediction may also include; comprising:

- a) Measuring of material density in a plurality of dimensions, for example using x-ray sensors,

b) Estimating other wood volume characteristics, including grain angle, growth ring angle, location in the tree from which the wood piece was cut, fiber quality including microfibril angle, and 3D geometry of the scanned piece,

c) Reducing clear wood equivalent density by the effect of the wood volume characteristics using relationships of these characteristics on mechanical behavior of wood.

d) Detecting size, location and classification of wood defects, including but not limited to, knots, biodeterioration, reaction wood, juvenile wood, manufacturing and drying defects, pith, pitch, wet pockets,

e) Further reducing clear wood equivalent density by the effect of wood defects in respective locations of occurrence and effect these characteristics on mechanical behavior of wood;

f) Constructing strength and stiffness models using clear wood density equivalent.

15 The further step of constructing clear zero grain angle wood equivalent as a first step in strength and stiffness prediction may also be included, comprising:

a) Measuring of material grain angle in a plurality of dimensions,

b) Constructing clear wood zero grain angle equivalent by assigning a nominal density value which is an average for a wood species whenever grain angle relative to a longitudinal axis of the piece is zero, and less wherever the grain angle deviates from zero and accordingly to grain angle effect on mechanical behavior of the wood piece,

c) Reducing clear wood equivalent density by the effect of the wood volume characteristics using theoretical and empirical relationships of these characteristics on mechanical behavior of wood,

d) Further reducing clear wood equivalent density by the effect of wood defects in their respective locations of occurrence and the effect on mechanical behavior of the wood piece, and

e) Constructing strength and stiffness models using clear wood density equivalent.

30

The further step may be included of estimating clear wood equivalent in an area of the wood piece occupied by a knot by virtually removing density occupied by a knot and replacing it by a density of clear wood, mechanically equivalent to the removed knot.

The sensors may include a sensor collecting pixel values from a corresponding matrix of pixels in the sensor, and wherein for every pixel density, d_{ij} , the method and software includes the step of computing clear wood equivalent, e_{ij} , using adaptive threshold clear wood density, a_{ij} , in the equation:

5
$$e_{ij} = \text{RemaingClearWood} + \text{KnotEquivalent}$$

wherein:

$$\text{RemaingClearWood} = a_{ij} - k_{ij} * K$$

i is virtual pixel index along the length of the wood piece

j is virtual pixel index transversely across the wood piece

10 K is knot density ratio, defined as a ratio of clear wood density to density of knot

knot density is difference between wood density d_{ij} and clear wood density

$$k_{ij} = d_{ij} - a_{ij}$$

15 KnotEquivalent is defined as clear wood density equivalent residing in knot volume,

$$\text{KnotEquivalent} = k_{ij} * K * M$$

wherein M is the material knot property ratio:

$$M = \text{Knot Property} / \text{Clear Wood Property}.$$

20 The step of computing e_{ij} may include substituting:

$$e_{ij} = a_{ij} + (d_{ij} - a_{ij}) * K * (M - 1).$$

The step of predicting strength and stiffness may include the step of estimating effect of the grain angle by decomposing the grain angle into running average and local deviation components, wherein the running average component is a function ($g_{ave}(GA)$) of running average grain angle along a length of the wood piece excluding grain deviations around knots, and wherein the local deviation component is a function ($g_{dev}(GA)$) of the grain angle defined as a difference between a local measured grain angle and the running average grain angle. The method and software further includes the step of computing grain angle effect functions $g_{ave}(GA)$ and $g_{dev}(GA)$ for determining the effect of grain angle on a material property wherein both $g_{ave}(GA)$ and $g_{dev}(GA)$ are computed according to the following equation:

25

30

$$g(GA) = \frac{1}{R \cdot \sin^n(GA) + \cos^m(GA)}$$

n and m are empirical constants, R is the ratio between the material property measured parallel to the grain versus the material property measured perpendicular to the grain. Optimizing constants R, n, and m are specific to the wood species corresponding to the wood piece.

a) The method and software further include the steps of:

applying the running average modification function ($g_{avg}(GA)$) to the clear wood equivalent density by multiplication according to:

$$e'_{ij} = e_{ij} * g_{avg}(GA_{ij})$$

b) modifying the grain deviation function ($g_{dev}(GA)$) to derive a further grain angle deviation modification function to avoid multiple density reduction due to knot detected in density according to:

$$g'_{dev}(GA_{ij}, k_{ij}) = g_{dev}(GA_{ij}) + (1 - g_{dev}(GA_{ij})) k_{ij}/T$$

wherein T is a constant threshold value density, and

c) applying the grain angle deviation modification function $g'_{dev}(GA_{ij}, K_{ij})$ to clear wood equivalent density by multiplication

$$e'_{ij} = e_{ij} * g'_{dev}(GA_{ij}, k_{ij}).$$

The method and software may further include the step of estimating a moisture content effect function, $m(MC)$, in the clear wood density equivalent by computing $m(MC)$ with a reference to 12% moisture content wherein

$$m(MC) = \text{either } A - B * MC \text{ for } MC < MC_{sat}, \text{ or}$$

$$m(MC) = m_{sat} \text{ for } MC \geq MC_{sat}$$

Where

$$B = (P - 1)/(0.12 - MC_{sat} - 0.12 * P)$$

$$A = 1 + 0.12 * B$$

$$m_{sat} = A - B * MC_{sat}$$

P is the ratio of a material property of interest when the wood piece is saturated with moisture to the same material property when the wood piece is oven-dry

$$P = S_{\text{sat}}/S_o$$

MC_{sat} is fiber saturation point moisture content within the percentage range 25 to 30%.

5 The method and software may further include the step of estimating a modulus of elasticity (MOE) profile of a section of the wood piece using estimation of modulus inertia computed from a clear wood density equivalent by:

(a) computing an inertia profile along a longitudinal axis of the wood piece according to:

$$10 \quad I_i = \Delta x^3 \sum_{j=1}^K (c_i - j)^2 \cdot e_{ij}$$

wherein the longitudinal axis is in an x-axis direction, and wherein Δx is a pixel increment in the x-axis direction, and wherein center of gravity is computed according to:

$$c_i = \frac{\sum e_{ij} \cdot j}{\sum e_{ij}}$$

and wherein e_{ij} is clear wood equivalent density;

15 (b) computing MOE within a longitudinal window on the wood piece, wherein $MOE_k = f(I_i, k)$,

and wherein $f(I_i, k)$ is a function that estimates the MOE in location k, using the inertia profile I_i , whereby MOE_k provides an estimate of the MOE along the board main axis, to provide an MOE profile. The function $f(I_i, k)$ may be estimated using

20 weights W_j according to:

$$f(I_i, k) = \sum_{j=1}^M W_j \cdot I_{k+i-M/2}$$

The function $f(I_i, k)$ may also be calculated as a close-form solution modulus of inertia profile according to:

$$25 \quad E_{\text{Est}} = D \frac{1}{K}$$

wherein

$$K = \Delta x^2 \left(\sum_{N/2} \sum_{N/2} y_i - \frac{1}{2} \sum_N \sum_N y_i \right)$$

Δx is a discrete increment in the direction of the x axis,

$$y_i = \frac{w_i}{J_i}$$

w_i is discrete representation of $w(x)$, and

5 J_i is I_i

The step of estimating modulus of elasticity from the MOE profile may use a low point or an average of the MOE profile.

10 The method and software may include the step of constructing clear wood density equivalent of a limited section of the wood piece, wherein the limited section is translated along the grain direction axis of the wood piece. The step of constructing clear wood density equivalent may include:

(a) computing minimum clear wood equivalent density profile in a window of
15 the wood piece and running the window along the grain direction axis of the wood piece such that the window combines adjacent weak areas

$$e_j^{MIN} = \text{Min}_{i=0}^{i=W-1} (e_{ij})$$

wherein i is pixel index within window, $i = 0 \dots W-1$, along the grain direction axis, wherein the grain direction axis is in the nominal grain direction of the wood
20 piece

j is index perpendicular to the grain direction axis,

(b) computing weighted clear wood equivalent density for the entire section

$$e = \sum_{j=1}^N w_j \cdot e_j^{MIN}$$

wherein w_j is a cross-sectional weight which is greater at edges of the wood
25 piece and reduced in the middle of the wood piece between the edges,

(c) computing tension strength (UTS) and bending strength (MOR) from e

$$UTS = f^{UTS}(e)$$

$$MOR = f^{MOR}(e)$$

Where f^{UTS} and f^{MOR} are empirical relationships between clear wood density and strength.

The strength functions f^{UTS} and f^{MOR} may be determined according to

$$5 \quad UTS = f^{UTS}(e) = A e^p$$

and

$$MOR = f^{MOR}(e) = B e^r$$

wherein A, p, B, r are empirical constants.

10 The method and software may also include the further step of estimating bending and tension strength of at least a portion of the length of the wood piece by determining a minimum of a lengthwise strength profile of the wood piece.

The method and software may further include the step of refining the model by optimization of model parameters to minimize prediction error. For example, the model
15 may be optimized for a particular wood species for particular commercial dimension lumber size.

In the method and software the step of collecting information relating to fiber quality may include the step of estimating fiber quality by measuring a vibration frequency of the wood piece, wherein the vibration frequency is a result of vibration induced only by
20 feeding of the wood piece in an infeed feeding the wood piece, for example between a plurality of infeed rolls, to the sensors and without any explicit means vibration-inducing impact means.

The method and software may further include the step of estimating bending and tension strength of the wood piece by measuring a vibration frequency of the wood piece
25 wherein the vibration frequency is a result of vibration induced only by feeding of the wood piece in an infeed feeding the wood piece to the sensors and without any explicit vibration-inducing impact means.

At least two pairs of infeed rolls and two pairs of outfeed rolls, respectively upstream and downstream of the sensors, may be employed. A non-contact optical scanner
30 may be employed to measure the vibration frequency, which may be measured by dividing the vibration signal into different sections corresponding to the support and constraint conditions of the wood piece on the infeed or the outfeed rolls. The support conditions may be unconstrained, semi-constrained, or fully-constrained.

In the method a parameter E may be calculated according to:

$$E = K f^2 m / I$$

wherein E is estimated MOE, K is a constant than contains the effect of the type of constraint, whether unconstrained, semi-constrained or fully constrained, as well as board span effect, I is a constant for a particular board cross-sectional size and m is distributed mass. m may be assumed constant, or measured, for example by a scanner using a radiation source.

In the method and software, the moisture content may be estimated using microwave measurement, or using microwave measurement and density estimation, and density characteristics may be measured by a scanner using a radiation source. The moisture content (mc) may be computed according to:

$$mc = K a^n$$

where K and n are empirical constants, and a is microwave amplitude. The microwave amplitude may be measured when an applied microwave radiation is polarized in a direction transverse to a longitudinal axis of the wood piece. The moisture content (mc) may also be computed according to:

$$mc = K a^n d^m$$

where K, m, and n are empirical constants, a is microwave amplitude, and d is density, which may be measured by a scanner using a radiation source. Moisture content and microwave amplitude may be corrected for temperature.

The lumber value of the lumber may be maximized by cutting lumber or end trimming lumber based on estimated modulus of elasticity profile, wherein increased lumber value of the lumber is achieved by trimming off a part of the lumber board having a grade reducing property.

The computer program product according to one aspect of the present invention includes computer readable program code means for causing refining the physical prediction model of the workpiece by computer readable program code means for causing optimization of model parameters to minimize prediction error. Input variables in the property (strength or stiffness) physical prediction model include collected board data and model parameters. The Predicted Property = $f(\text{Model Parameters}, \text{Board Data})$, where, $\text{Model Parameters} = (p_1, p_2, p_3, \dots, p_N)$ and *Board Data* is the sensor information gathered about the wood piece as set out above. The error to be optimized is a measure of the

difference between predicted property and observed property, for example absolute value of the difference, that is $\text{Error} = \text{AbsoluteValue}(\text{Predicted Property} - \text{Observed Property})$. The optimization of model parameters is achieved by minimizing combined error of a large sample of boards. For example, combined error for a sample of boards is a sum of the errors, as defined above, that is $\text{SumOfErrors} = \text{Sum}(\text{Error}_i)$. Combined error could be quantified in various ways, including R-square, root-mean-squared error, etc. Optimization is implemented by varying values of *Model Parameters* so the combined measure of the error for a sample is minimized. Various optimization algorithms may be employed, for example genetic algorithm, random walk, direction set (Powell's) method, etc as would be known to one skilled in the art.

Brief Description of the Drawings

In the accompanying drawings, in which like reference characters designate the same or similar parts throughout the several views:

FIGURE 1 is a diagrammatic view of multiple sensors measuring attributes and properties of a board for physical modeling by a processor algorithm to predict strength and stiffness of the board as algorithm outputs.

FIGURE 1A illustrates board coordinates, showing the main axis (X) along the nominal grain angle direction.

FIGURE 1B illustrates a board divided into a 3-dimensional grid of discrete elements, showing index notation for different directions.

FIGURE 1C illustrates a board divided into a 2-dimensional grid of discrete elements, showing notation of clear wood equivalent elements e_{ij} and a section of length W taken from it to estimate strength assigned a location in the center of the section.

FIGURE 1D shows an example of a density and clear wood equivalent profile for a virtual detector (pixels of the same index j) along the board main axis X. The upper-most graph (with peaks pointing upwards) show actual density profile with its reference density profile below. The density peaks correspond to knots. The lower-most profile (with peaks pointing downwards) shows clear wood equivalent density.

FIGURE 1E shows an example of predicted tension and bending profiles along the board main axis X, showing the lowest point (minimum) computed from a moving section along the board main axis.

FIGURE 1F shows an example of moment of inertia profile with a section of a

board used to compute modulus of elasticity (MOE) for a given location where prediction of modulus of elasticity (MOE) is computed using moment of inertia within a section of length s that moves along the board main axis.

FIGURE 1G illustrates loading conditions assumed for computation of predicted
5 modulus of elasticity (MOE) using moment of inertia within a section of length s .

FIGURE 2A illustrates steps involved in clear wood density computing for a density cross-section showing original density d_{ij} and adaptive threshold a_{ij} .

FIGURE 2B illustrates steps involved in clear wood density computing for a density cross-section, showing clear wood equivalent density e_{ij} .

10 FIGURE 3 are linear and nonlinear models of a function reflecting effect of moisture content $m(\text{MC})$.

FIGURE 3A is a moisture content prediction model showing predicted vs. oven-dry moisture content for southern yellow pine (SYP).

15 FIGURE 4 illustrates a linear grading machine geometry, showing infeed wheel sets #1 and #2, outfeed wheel sets #1 and #2, and 3D-profile sensor.

FIGURE 5 illustrates board behavior as the board passes through the linear grading machine. Characteristic points A, B, C, and D define different sections in the linear profile sensor profile corresponding to different support conditions of the board, wherein:

- a) in FIGURE 5A the board leading end is at point A
- 20 b) in FIGURE 5B the board leading end is at point B
- c) in FIGURE 5C the board leading end is at point C
- d) in FIGURE 5D the board leading end is at point D.

FIGURE 6 is continued board behavior as it passes through the linear grading
25 machine having characteristic points E, F, and G and a board adjustment before and after the characteristic point F, wherein:

- a) in FIGURE 6A the board trailing end is at point E
- b) in FIGURE 6B the board trailing end is at point F
- c) in FIGURE 6C the board trailing end has passed point F
- 30 d) in FIGURE 6D the board trailing end is at point G.

FIGURE 7 is 3D-profile sensor profile segmented into different sections using characteristic points of FIGURES 5A-D and 6A-D.

Detailed Description of Embodiments of the Invention

We have developed a machine to predict the strength and stiffness of wood based on a physical model using several sensing technologies. A physical model is an algorithm that relates the sensor information to the strength/stiffness of the material based on physical properties of the material and other characteristics, such as defects. The machine can integrate many sensing technologies into a single model and provides differing accuracy prediction based on the types and number of sensors used. In one embodiment, this technology builds on an X-ray based strength-grading machine, such as sold by Coe Newnes/McGehee ULC under the trademark XLG (X-ray Lumber Gauge).

The following physical aspects of wood effect strength and stiffness of wood directly: wane, moisture content, Modulus of Elasticity including whether measured flatwise or edgewise, growth ring thickness or density (rings/inch), grain angle deviation, density, knots (location, density, type and size), location in the tree from which the wood was cut, fiber quality, such as microfibril angle, juvenile wood, biodeterioration, etc., reaction wood species, manufacturing and drying defects, such as sawcuts, checks, shake, etc. and, size of actual cross-section.

These wood aspects are measured or predicted with various sensing technologies and the data is used to predict the wood strength and stiffness. The reason to choose a physical model over other techniques such as a neural network, regression, or functional approximation model, is the stability and low training requirements. The model is based on the physical characteristics of the wood and how they affect the strength and stiffness directly rather than a statistical model. The sensor technologies added together improve the ability of any one sensor to predict strength and stiffness.

The object is to have the predicted wood characteristics match the observed characteristics. The sensor technologies that can be used include but are not limited to the following: density map, moisture content, slope of grain map, growth ring measurements, dynamic wood bending for stiffness measurement, dynamic oscillation to determine stiffness, wood fiber quality determination (color vision, gray scale, infra-red, etc), determination of species, profile measurement, location wood is cut from in the tree, and mechanical wane propagation measurement.

Combining some or all of these physical measurements, for example as combined according to the detailed methodology described below, leads to a better-predicted wood strength and stiffness accuracy.

With respect to the following description then, it is to be realized that the optimum
 5 relationship between the components and steps of the invention, to include variations in method, components, materials, shape, form, function and manner of operation, assembly and use, are deemed readily apparent and obvious to one skilled in the art, and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present invention.

10 **Clear Wood Equivalent**

Clear wood equivalent (CWE) is used as an input to specific strength and stiffness models. Various prediction models may be used or developed based on this concept, such as prediction of ultimate tensile strength, modulus of rupture, etc. The CWE method approximates equivalent properties of a section of material in terms of density.

15 Wood, in a coordinate system such as seen in FIGURE 1A, is divided into a grid of virtual pixels (rectangular section) in the face plane or 3-dimensionally, as illustrated in FIGURE 1B. The size of the virtual pixels is configurable so as to be optimized. Initially a reference density from calibrated X-ray measurement is assigned to a pixel. Reference density is taken from density adaptive threshold. Following this, the initial density is
 20 modified by various wood characteristics, among which the most important is knot modification. The resulting density is equivalent to clear wood. In this context clear wood is defined as straight grained, defect-free, with a reference moisture content of 12%. FIGURE 1D shows an example of an actual density profile (ADP) along with its corresponding reference density profile (RDP) and corresponding clear wood equivalent
 25 (CWE) density profile along the main axis X. The equivalent to clear wood is then used directly for strength and stiffness using various algorithms, known relationships, etc.

Some of the following steps may be in used in clear wood equivalent density approximating of a virtual pixel:

- a) Start with reference density (adaptive threshold) at a virtual pixel.
- 30 b) modify initial density for knots by considering presence of a knot in a location if the difference between the reference and actual density of the knot is non-zero.

c) segment into regions so that a region contains a knot, use the segmented regions to recognize the knots region or regions.

Different modification functions are used for the following knot types: sound through knot, sound edge knot, sound intermediate knot, loose through knot, loose edge knot, loose intermediate knot.

Knot modification uses a concept of replacing a knot by its equivalent in terms of fiber strength or stiffness. This involves virtually removing the knot, computing remaining clear fiber volume, computing volume of the removed knot and adding the strength/stiffness equivalent of the knot to clear fibers. For every pixel density, d_{ij} , clear wood equivalent, e_{ij} , is computed using adaptive threshold a_{ij} (see Figures 2a and 2b)

$$e_{ij} = \text{RemainClearWood} + \text{KnotEquivalent} \quad (1)$$

Where,

$$\text{RemainClearWood} = a_{ij} - k_{ij} * K \quad (2)$$

i is virtual pixel index along wood length (virtual line index)

j is virtual pixel index across wood length (virtual detector index)

K is knot density ratio, defined as a ratio of Clear Wood Density to Knot Density and knot density is

$$k_{ij} = d_{ij} - a_{ij} \quad (3)$$

KnotEquivalent is defined as clear wood density equivalent residing in knot volume,

$$\text{KnotEquivalent} = k_{ij} * K * M \quad (4)$$

Where M is property (stiffness or strength) knot ratio

$$M = \text{Knot Property} / \text{Clear Wood Property} \quad (5)$$

The above relationships may be simplified to

$$e_{ij} = a_{ij} + k_{ij} * K * (M - 1) \quad (6)$$

or

$$e_{ij} = a_{ij} + (d_{ij} - a_{ij}) * K * (M-1) \quad (7)$$

Grain Angle Modification

- 5 Grain angle is measured or estimated using one or more of the following techniques: microwave, optical, tracheid effect on face plane, 2D angle, tracheid effect on face plane and edges, 3D angle, growth ring pattern analysis with vision images (color or gray-scaled images), tracheid effect and growth ring pattern analysis with vision images. This algorithm accounts for the presence of a knot and grain deviation in the same location.
- 10 Grain angle is decomposed into two components: local average, and, local deviation.

Grain angle (GA) effect function for both average and the deviation, $g(GA)$, reflects the relationship of grain angle vs. strength (or stiffness). This is derived from Hankinson's formula (Bodic 1982),

$$g(GA) = \frac{1}{R \cdot \sin^n(GA) + \cos^m(GA)} \quad (8)$$

- 15 where n, m , are empirical constants, initially $n = m = 2$, (optimized).

R is the ratio between the property of interest (strength or stiffness) parallel to perpendicular to the grain.

- Constants R, n , and m are to be optimized, with a restriction that the $g(GA=0) = 1$ and $1 \geq g(GA) > 0$ for any GA . Modification function $g(GA)$ is applied to CWE density by
- 20 multiplication of

$$e'_{ij} = e_{ij} * g(GA_{ij}) \quad (9)$$

- In case of grain deviation, $g(GA)$ is further modified to account for a knot in the
- 25 same location to eliminate a multiple CWE density reduction

$$g_{dev}(GA_{ij}, k_{ij}) = g(GA_{ij}) + (1 - g(GA_{ij})) k_{ij}/T \quad (10)$$

- Where, T is a threshold value in terms of density.
- 30

Important to the property of this relationship is if $k_{ij} = T$, then grain deviation modification has no effect:

$$g_{dev}(GA_{ij}, k_{ij} = T) = 1 \quad (11)$$

Both local average and local deviation are applied independently to CWE density.

5

Moisture content modification

The moisture content effect function, $m(MC)$, reflects the known effect of moisture content on strength or stiffness. This relationship is modeled as a linear (downward) for $MC < MC_{sat} \approx 25\%$, and constant, $m(MC) = m_{sat}$, for $MC \geq MC_{sat}$. Ratio $m(MC_{sat})/m(0)$ corresponds to the ratio between a property (MOE, MOR, UTS) at saturation to oven dry, $P = S_{sat}/S_o$. Based on literature, this ratio is about 0.5 for UTS and MOR and 0.7 for MOE. Since the basis for our computations is property at $MC = 12\%$ then $m(12\%) = 1.0$.

Therefore the requirements for the $m(MC)$ are:

- 15 a. MC effect function is linear with a negative slope in the MC range from zero to saturation, and constant afterwards,

$$m(MC) =$$

$$\begin{cases} A - B * MC & \text{for } MC < MC_{sat} \\ m_{sat} & \text{for } MC \geq MC_{sat} \end{cases} \quad (12)$$

- 20 b. Property ratio

$$P = \frac{S_{sat}}{S_o} = \frac{m(0)}{m_{sat}} \quad (13)$$

Initially,

$$P = 0.5 \text{ for MOR and UTS (strength)} \quad (14)$$

- 25 $P = 0.7$ for MOE (stiffness)

- c. MC effect function is unity at nominal moisture content of 12%

$$m(12\%) = 1.0 \quad (14a)$$

- 30 Solution for $m(MC)$, linear model

Solving equations (12) to (15), gives

$$B = (P - 1)/(0.12 - MC_{sat} - 0.12 * P) \quad (15)$$

and

$$A = 1 + 0.12 * B \quad (15a)$$

5 For example, for $P = 0.5$ and $MC_{sat} = 0.25$,

$$A = 1.3158$$

$$B = 2.632$$

$$m(MC_{sat}) = 0.6579$$

10 FIGURE 3 shows the linear model using the above constants and two nonlinear models:

$$m(MC) = 0.65 + 0.3 * e^{-12 * MC} \quad (16)$$

$$m(MC) = 0.65 + 9.29^{-5.45 * MC} \quad (17)$$

15

Pith modification

$$e'_{ij} = e_{ij} * p(\text{amount of pith present}) \quad (18)$$

Where $p()$ represents effect of pith on strength and stiffness.

20 **Growth ring thickness modification. Predicted based on X-ray and Vision**

$$e'_{ij} = e_{ij} * g(\text{growth ring thickness}) \quad (19)$$

Where $g()$ represents effect of growth ring thickness on strength and thickness

Place within tree modification.

25 Place within tree quality parameter is predicted based various scanning technologies

$$e'_{ij} = e_{ij} * t(\text{place within tree modification quality parameter}) \quad (20)$$

Where $t()$ is a function representing effect of position within tree.

30 **Other wood characteristics modification, rot, wane, check, resin content, compression wood, etc.**

This set of modifications follow similarly to the modification analogues set out above for grain angle, moisture content, etc.

3D Clear Wood Equivalent

This approach expands the two-dimensional CWE model as described above to three-dimensions (3D). Virtual pixels are defined in 3D. Knots, checks, and other defect modifications are done based on 3D-defect detection. Other multiple sided defects such as checks are also included. This includes two approaches:

- a) Density collected in 2D, knots, checks modifications entered as 3D, resulting with 3D grid of clear wood equivalent density
- b) Density collected in 3D with a CT scanner, knots, checks, and other 3D-defect modifications entered as 3D objects, resulting with 3D grid of clear wood equivalent density.

Clear Wood Equivalent Based on Grain Angle

This approach follows the one of CWE density described to this point, but the density is replaced with grain angle. First a grain angle is assigned to a grid element. Then the GA is modified by density, knots, moisture content, and other defects. Grain angle CWE is then used in actual models to predict strength and stiffness. This refers primary to lumber grading, but is not limited to this type of products.

Stiffness Prediction Using Moment of Inertia

Stiffness (Modulus of Elasticity) is predicted based on approximated cross sectional moment of inertia J_i computed from clear wood equivalent model.

In general, moment of inertia I is defined in x direction for any cross-section with an area A (Popov 1968)

$$I = \int_A (c - x)^2 dA \quad (21)$$

Where c is center of gravity of the cross-section A .

In our case, I is approximated by J_i in terms of density, reflecting both geometry of the cross-section as well as local stiffness

$$J_i = \Delta x^3 \sum_{j=1}^N (c_i - j)^2 \cdot e_{ij} \quad (22)$$

Where Δx represents pixel increment in x -axis direction and center of gravity is given as

$$c_i = \frac{\sum e_{ij} \cdot j}{\sum e_{ij}} \quad (23)$$

To increase processing speed, c_i does not have to be computed for every cross-section, but assumed to be equal to nominal center of the cross-section.

5 Two different approaches are given here to compute MOE from the J_i profile. In both cases MOE is computed on a section of J_i profile. The section is then moved along the board main axis X and MOE computed for another section of the board, as illustrated in FIGURE 1F. This procedure yields a MOE profile along the main axis X.

10 First, a simple solution is given where MOE is simply weighted average of the J_i

$$MOE = \sum_{i=1}^M W_j \cdot J_j \quad (24)$$

Where W_j is optimized windowing (sectioning) function.

Although, the equation (24) provides a simply and fast way of MOE prediction, a
15 more sound but slower approach is to derive MOE directly from moment of inertia I. Following derivation follows well-known theory of mechanical behavior of solids (Popov 1968).

Moment of inertia is assumed to be a variable quantity within a span s, as shown in
FIGURE 1F. For a board section loaded with force F, as in FIGURE 1G, equations for
20 moments are

$$M(x) = Fw(x) \quad (24a)$$

Where

$$w(x) = \frac{x}{2} \quad \text{for } 0 < x \leq s/3 \quad (24b)$$

$$w(x) = \frac{s}{6} \quad \text{for } s/3 < x \leq s/2 \quad (24c)$$

$$25 \quad w(x) = \frac{1}{2}(s - x) \quad \text{for } s/2 < x \leq s \quad (24d)$$

The basic equation for beam deflection is

$$\frac{M(x)}{E(x)I(x)} = \frac{d^2V^2(x)}{dx^2} \quad (24e)$$

Where $E(x)$ represent MOE in location x ,

$I(x)$ moment of inertia profile,

$V(x)$ deflection profile.

- 5 A further simplification combines E and I into one quantity $J(x)$, which reflect a local stiffness of the cross-section.

$$J(x) = E(x) I(x) \quad (24f)$$

The equation (24e) simplifies into

$$10 \quad \frac{M(x)}{J(x)} = \frac{dV^2(x)}{dx^2} \quad (24g)$$

Following, the equation (24g) is solved for deflection $V_{\max}$ at $x = s/2$ using direct integration method, applying boundary conditions, and converting to discrete format gives

$$K = \frac{V_{\max}}{F} = \Delta x^2 \left(\sum_{N/2} \sum_{N/2} y_i - \frac{1}{2} \sum_N \sum_N y_i \right) \quad (24h)$$

Where Δx in a discrete increment in direction of the X axis,

$$15 \quad y_i = \frac{w_i}{J_i} \quad (24i)$$

w_i is discrete representation of $w(x)$,

J_i is discrete representation of $J(x)$, the moment of inertia estimation computed from clear wood equivalent density.

- 20 On the other hand, for a uniform beam with loading conditions as in FIGURE 1g, the solution for E is

$$E = \frac{23Fs^3}{1296IV_{\max}} \quad (24j)$$

or for the same cross-section and span (24j) simplifies to

$$25 \quad E = D \frac{F}{V_{\max}} \quad (24k)$$

Where D is a constant representing a size of a board cross-section.

Therefore a quantity to estimate is $\frac{F}{V_{\max}}$ only.

This, compared with the solution (24h), yields final MOE estimation E_{est}

$$E_{\text{Est}} = D \frac{1}{K}$$

Strength Prediction

5 Strength is predicted lengthwise for a section (window) along nominal main board axis X (nominal grain direction). Therefore a particular predicted strength is assigned to a center of a window lengthwise, as shown in FIGURE 1E. These sections may overlap resulting with a complete strength profile for a wood product, such as lumber. Window length correspond to approximate size of typical wood fracture and generally increases
10 with lumber width size (greater width size, greater the window). The final strength value assigned to a tested product is minimum strength within the strength profile.

Strength is computed on the basis of a running window along wood main axis (length), as illustrated in FIGURE 1C, involving following steps:

a) get minimum CWE within a longitudinal slice, e_j^{MIN} where the slice consists
15 of virtual pixels in the same width position

$$e_j^{\text{MIN}} = \text{Min}_{i=0}^{i=W-1} (e_{ij}) \quad (25)$$

Where i is pixel index within window, $i = 0 \dots W-1$

and W is window size in virtual lines

b) compute overall CWE density for the window as a weighted sum

$$20 \quad e = \sum_{j=1}^K w_j \cdot e_j^{\text{MIN}} \quad (26)$$

Where w_j is cross-sectional weight, greater at wood edges and less in the middle. The weight function is different for UTS and MOR and in general subject to model optimization.

25

c) computes strength from CWE density tension strength (UTS) relationship

$$UTS = f^{\text{UTS}}(e) \quad (27)$$

And bending strength (MOR)

$$MOR = f^{MOR}(e) \quad (28)$$

5 where f^{UTS} and f^{MOR} are optimized relationships between CWE and UTS and MOR.

The density to tension and bending strength functions are based on experimental data conducted on clear wood specimens and/or are in general the subject of model optimization.

In particular, the following model may be used

$$UTS = A e^p = f^{UTS}(e) \quad (29)$$

15 and

$$UTS = B e^r = f^{UTS}(e) \quad (30)$$

where A, p, B, r are empirical (optimized) constants.

20 d) Final wood strength is a minimum of all windows strength values

MC modeling based on Microwave and X-ray density measurement

Moisture content is predicted based on microwave and/or X-ray density, for:

(a) Microwave amplitude, and in particular: amplitude when microwave is polarized in transverse direction, amplitude when microwave is polarized in longitudinal direction, in form

$$mc = K a^n, \quad (31)$$

where K and n are empirical constants, and a is microwave amplitude.

30 (b) Microwave amplitude and X-ray density, and in particular, amplitude when microwave is polarized in transverse direction and X-ray density, amplitude when microwave is polarized in longitudinal direction and X-ray density, in form:

$$mc = K a^n d^m \quad (32)$$

where K, m, and n are empirical constants, a is microwave amplitude, and d is X-ray density.

5 **Model Optimization**

Most models described here require optimization of the parameters (constants). Initial values for these parameters are taken from literature, using known relationships or from empirical data. Fine-tuning of these values for a specific species/size involves parameter optimization for maximum correlation with actual strength or stiffness,
10 minimum prediction error, etc.

Any method for multidimensional function optimization may be used, including genetic algorithms, random walk, and similar techniques, Powell's methods, and Gradient methods.

Models may be optimized for:

- 15 a) All sizes and species,
- b) Same sizes of the same species or species group, and
- c) Particular size and species.

Stiffness Estimation from Machine Induced Wood Vibration

Vibration of a wood piece as it passes through a grading machine 10 is used to
20 estimate stiffness (MOE). Vibration profile may be collected with a laser/camera scanner, here referred to as a 3D sensor. Vibration is induced by machine feeding mechanics.

Machine Geometry and Wood Dynamics

As wood behavior is linked with machine geometry and its position, the 3D-profile is segmented into different sections limited with characteristic points.

25 A simplified grading machine geometry is show in FIGURE 4. Wheel sets 11, 12, 13, and 14 follow the direction of the lumber flow X'.

Wood piece 15 enters the machine from right to left, passing through wheel sets 11 and 12 and into the field of view of 3D 15 sensor as shown in Figures 4 and 5A-D. First collected profile point is at characteristic point A in the field of view of sensor 15. From
30 point A until the wood meets in feed guide 13a (characteristic point B), the leading end of the wood piece is fully unconstrained or free. This defines a first 3D profile section, AB.

Following on downstream in direction X ' as seen in Figures 6a-6d, more characteristic points are defined as follows, where, at point:

- C the leading end of wood 15 meets wheel set 13
- D the leading end of wood 15 meets wheel set 14
- 5 E the trailing end of wood 15 leaves wheel set 11
- F the trailing end of wood 15 leaves wheel set 12
- G the trailing end of wood 15 leaves 3D sensor 16
- and sections,
- AC unconstrained
- 10 CD semi-constrained
- DE fully-constrained
- EF semi-constrained
- FG unconstrained.

15 From Figures 5a-5d and 6a-6d, it may be noted that only sections AB (or AC) and FG is statically undistorted by the machine. Because of unconstrained conditions, a free vibration takes place in these sections.

For the "*S-shaped*" wood in Figures 6A-D, one could expect a wood behavior, resulting with the following 3D profile:

- 20 a. In section AC (or AB) unconstrained, Z is less than the reference (base) line X", and free vibrations with large amplitude take place. The frequency of vibration decreases because of increasing span.
- b. As the wood passed through characteristic point B or C, it is adjusted up, resulting with Z values greater than reference in semi-constrained section CD. Vibration
- 25 amplitude in this section is somewhat reduced and higher in frequency than in section AB.
- c. In fully-constrained section DE, wood behavior is somewhat undefined. However because of the constrained condition, reduced amplitude and increased frequency is expected.

3D Profile Sections

30 The scenario of wood behavior and a resulting 3D profile is put to the test by segmenting the profile into sections using characteristic points and comparing the expectations with the actual wood shape. Figure 7 shows the 3D profile of FIGURE 5A-D and 6A-D with characteristic points and trend lines for every section. The characteristic

points were defined based on machine geometry. For example, the distance between point A and C correspond to the distance between 3D sensor 16 and center of the wheel set 13. Points A, B, C, and D were measured in reference to the start of 3D-profile sensor profile whereas points G, F, and E were measured in reference to the end of the 3D-profile.

- 5 Visual examination of the segmented profile in Figure 7 confirms presence of distinct sections in the signal. Expected frequency and amplitude of unconstrained sections AB and FG, adjustments as points B, (or C), and F, and relatively leveled fully constrained section DE are confirmed.

Free Vibration of the Wood

- 10 Assuming a uniform cantilevered beam model, the lowest mode of vibration will have frequency

$$f = 2\pi (1.875)^2 (EI/ma^4)^{1/2} \quad (38)$$

Where

- 15 $\pi = 3.14$

E is elastic modulus

a is the span

I wood cross-sectional moment of inertia

m is distributed mass.

20

- Frequency therefore is strongly affected by the span, as f is proportional to $1/a^2$. Because span changes as the wood passes through the machine, the vibration frequency decreases in the start section (AB) and increases in end section (FG). This explains 3D signals at the wood start and the end shown in Figures 5A-D. This equation may be used for stiffness extraction.

Frequency for the semi-constrained and full-constrained conditions will have a more complex solution. However, the general relationship to E, I, and m, is similar, and sufficient to construct E (MOE) prediction model in general form.

$$E = K f^2 m / I \quad (39)$$

- 30 where K is a constant than contains effect of type of constraint as well as span a effect. I is constant for a particular lumber size and m could be also assumed constant or measured, with X-ray for example.

As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

WHAT IS CLAIMED IS:

1. A lumber grading apparatus comprising:
 - an infeed having at least a first pair of opposed feed members positioned along a flow path;
 - an outfeed having at least a second pair of opposed feed members positioned along the flow path downstream of the first pair, such that the first and second pairs are separated by a gap, wherein the infeed and the outfeed are collectively configured to transport a piece of lumber lineally in a first direction along the flow path between the corresponding feed members; and
 - a first non-contact sensor positioned to detect the piece of lumber at a first location between the first and second pairs of opposed feed members and configured to measure vibrations of the piece of lumber as the piece of lumber moves through the first location with said piece of lumber between the feed members of one or both of the first and second pairs of feed members, wherein the vibrations are induced only by transportation of the piece of lumber by the feed members.
2. The lumber grading apparatus of claim 1, wherein the first non-contact sensor is a laser profile sensor.
3. The lumber grading apparatus of claim 2, wherein the feed members are feed rolls, the infeed further includes a third pair of opposed feed rolls upstream of the first pair, and the outfeed further includes a fourth pair of opposed feed rolls downstream of the second pair.
4. The lumber grading apparatus of any one of claims 1-3, further including a non-volatile computer readable medium having stored thereon computer-executable instructions operable, upon execution by a processor, to cause the processor to calculate an estimated stiffness of the wood piece based at least on data from the first non-contact sensor.
5. The lumber grading apparatus of any one of claims 1-3, further comprising a second non-contact sensor configured to measure a material characteristic of the piece of lumber as the piece of lumber is transported along the flow path in the first direction.

6. The lumber grading apparatus of claim 4, wherein the second non-contact sensor includes a vision camera.
7. The lumber grading apparatus of claim 4, wherein the second non-contact sensor includes an X-ray sensor.
8. The lumber grading apparatus of any one of claims 5-7, further comprising a non-volatile computer readable medium having stored thereon computer-executable instructions operable, upon execution by a processor, to cause the processor to
 - calculate an estimated stiffness of the wood piece based at least on data from the first non-contact sensor, and
 - calculate an estimated strength of the piece of lumber based at least on data from the second non-contact sensor.
9. The lumber grading apparatus of claim 4 or claim 8, further including a microwave sensor, wherein the computer-executable instructions are further operable, upon execution by the processor, to cause the processor to calculate a moisture content or grain angle of the piece of lumber based at least on data from the microwave sensor.
10. The lumber grading apparatus of any one of claims 4, 8, or 9, wherein the computer-executable instructions are further operable, upon execution by the processor, to cause the processor to calculate a three-dimensional geometric profile of the piece of lumber based at least on data from the first non-contact sensor.
11. The lumber grading apparatus of any one of claims 4, 8, 9, or 10, wherein the computer-executable instructions are further operable, upon execution by the processor, to cause the processor to estimate one or more additional wood characteristics based on the data from at least one of the non-contact sensors and to calculate the estimated strength or stiffness of the piece of lumber based at least in part on the one or more additional wood characteristics.

12. A method of grading a piece of lumber, the method comprising:

feeding the piece of lumber lineally along a flow path between one or more first pairs of opposed feed members and one or more second pairs of opposed feed members positioned downstream of the first pair along said flow path;

using a first non-contact sensor to measure, within a field of view located downstream of the one or more first pairs of opposed feed members and upstream of the one or more second pairs of opposed feed members, vibrations of the piece of lumber that are induced only by feeding the piece of lumber between the pairs of opposed feed members; and

estimating a stiffness of the piece of lumber based at least on vibration measurements obtained by the first non-contract sensor.

13. The method of claim 12, wherein the first non-contract sensor is a laser profile sensor.

14. The method of claim 12 or claim 13, wherein the first one or more pairs of opposed feed members includes a first pair of feed rolls and a second pair of feed rolls located downstream of the first pair of feed rolls, the second one or more pairs of opposed feed members includes a third pair of feed rolls and a fourth pair of feed rolls located downstream of the third pair of feed rolls, and the field of view is between the second pair of feed rolls and the third pair of feed rolls.

15. The method of claim 14, wherein the vibration data includes a first frequency measured while a leading end of the piece of lumber is between the second pair of feed rolls and the third pair of feed rolls, a second frequency measured while the piece of lumber is between both the second pair of feed rolls and the third pair of feed rolls, and a third frequency measured while a lagging end of the piece of lumber is between the second pair of feed rolls and the third pair of feed rolls.

16. The method of claim 15, wherein estimating the stiffness of the piece of lumber includes using at least one of the frequencies to estimate a modulus of elasticity of a corresponding portion of the piece of lumber according to:

$$E=Kf^2m/I$$

wherein

E is estimated MOE,

K is a constant than contains the effects of the type of constraint and board span, wherein the type of constraint is unconstrained, semi-constrained or fully constrained,

f is frequency,

I is a constant for a particular board cross-sectional size, and

m is distributed mass.

17. The method of claim 15 or claim 16, wherein estimating the stiffness of the piece of lumber includes using the first frequency or the third frequency to estimate a modulus of elasticity of a corresponding portion of the piece of lumber according to:

$$f=2\pi(1.875)^2(EI/ma^4)^{1/2}$$

wherein

f is frequency,

Pi=3.14,

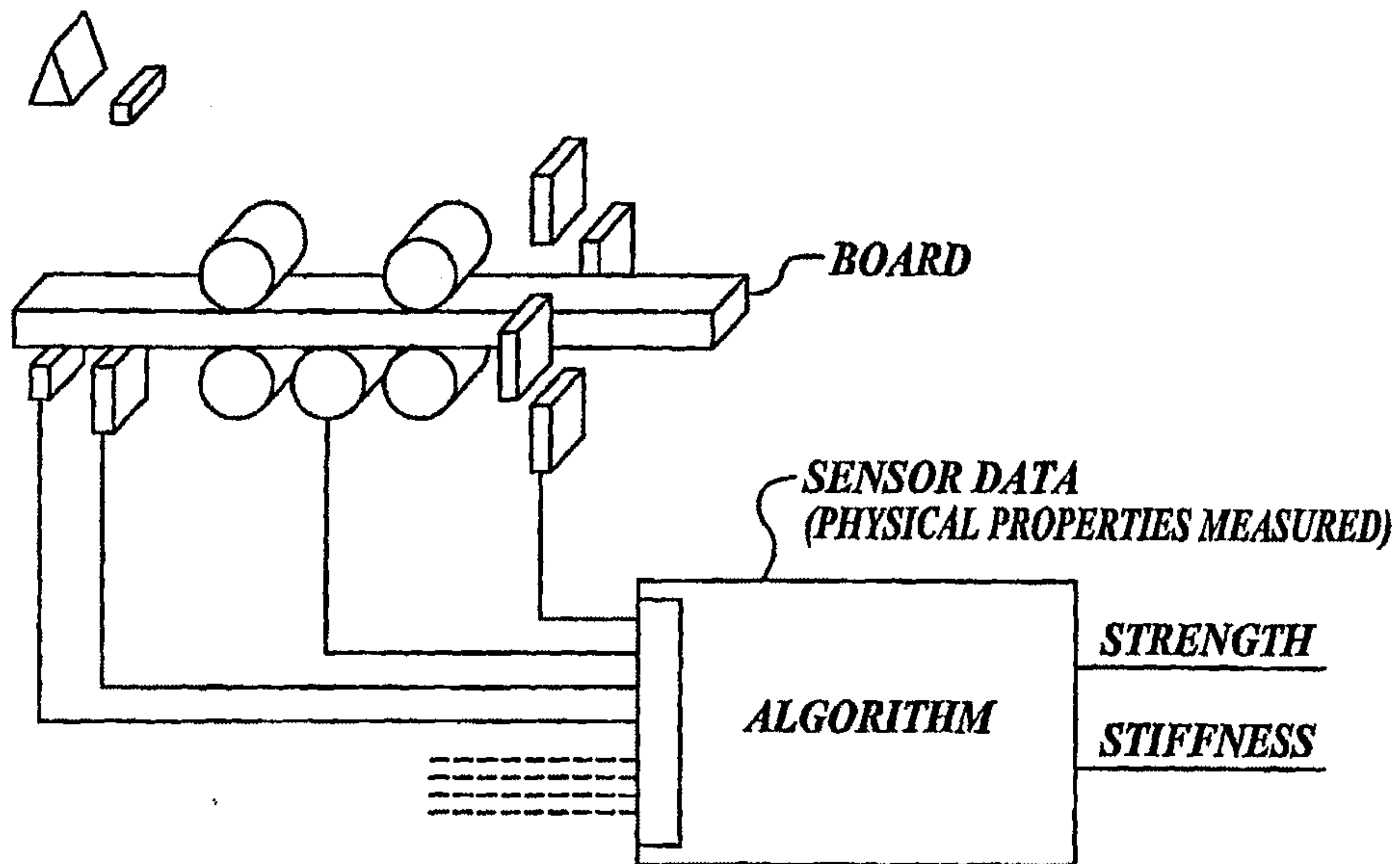
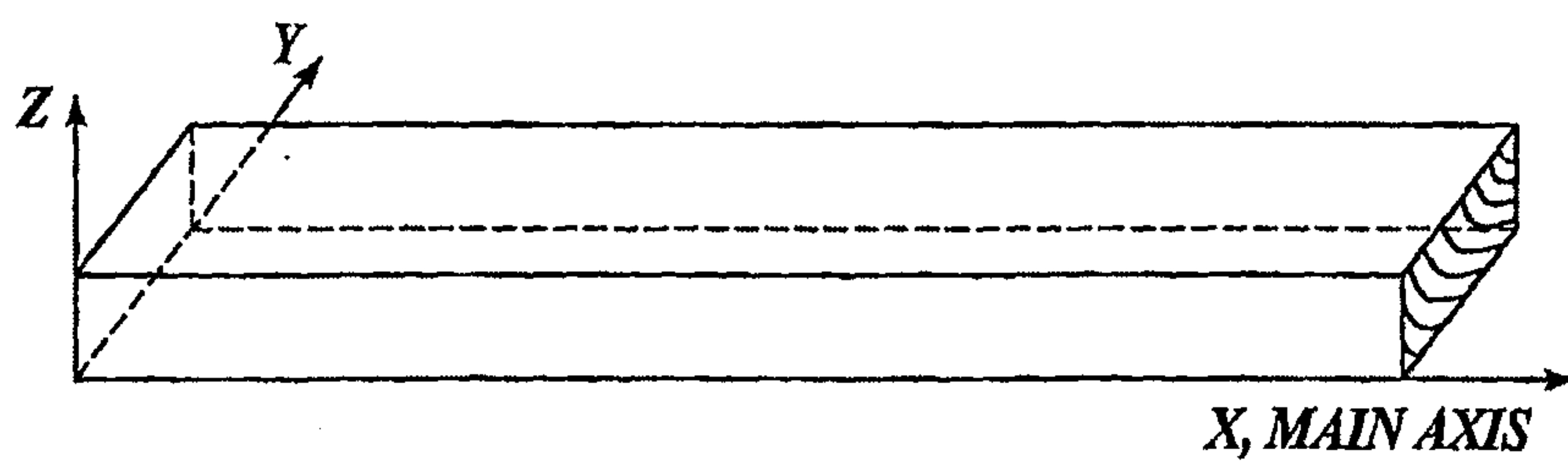
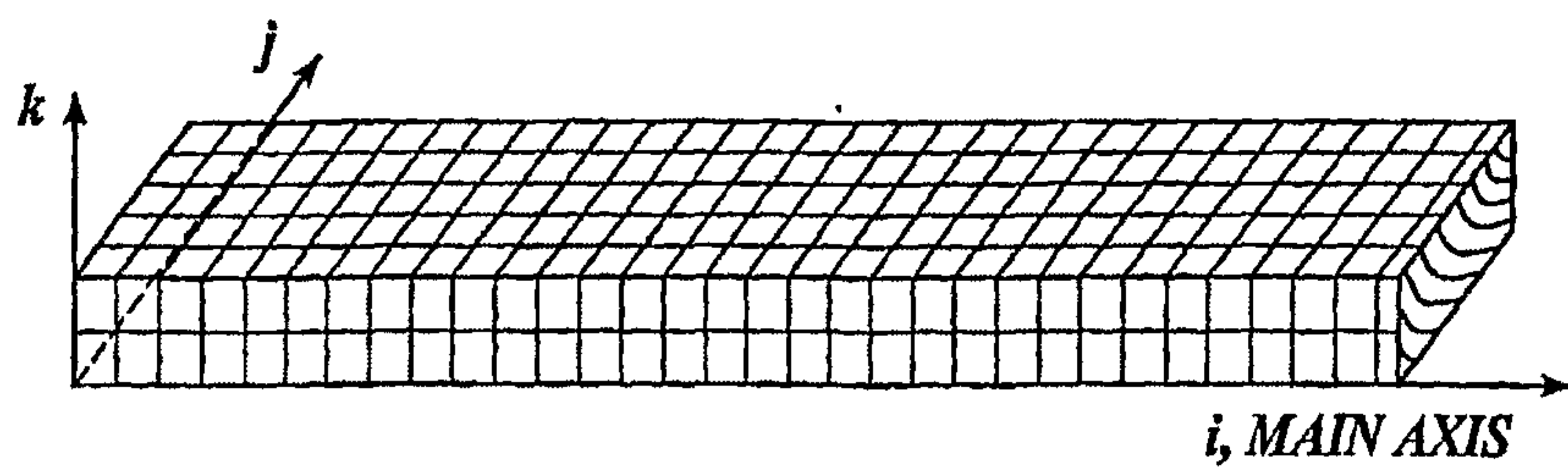
E is elastic modulus,

a is span,

I is wood cross-sectional moment of inertia, and

m is distributed mass.

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**FIG. 1****FIG. 1A****FIG. 1B**

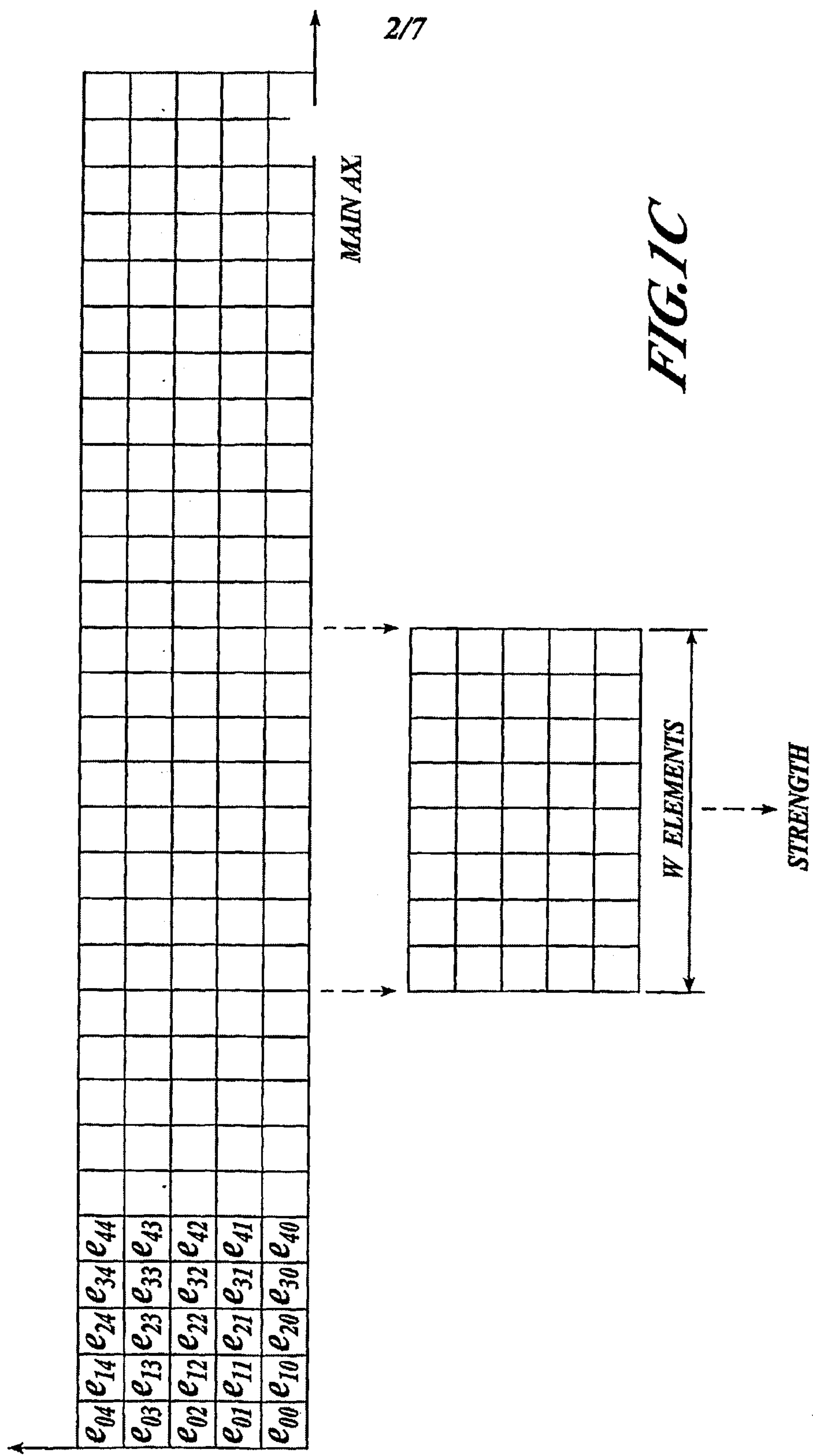
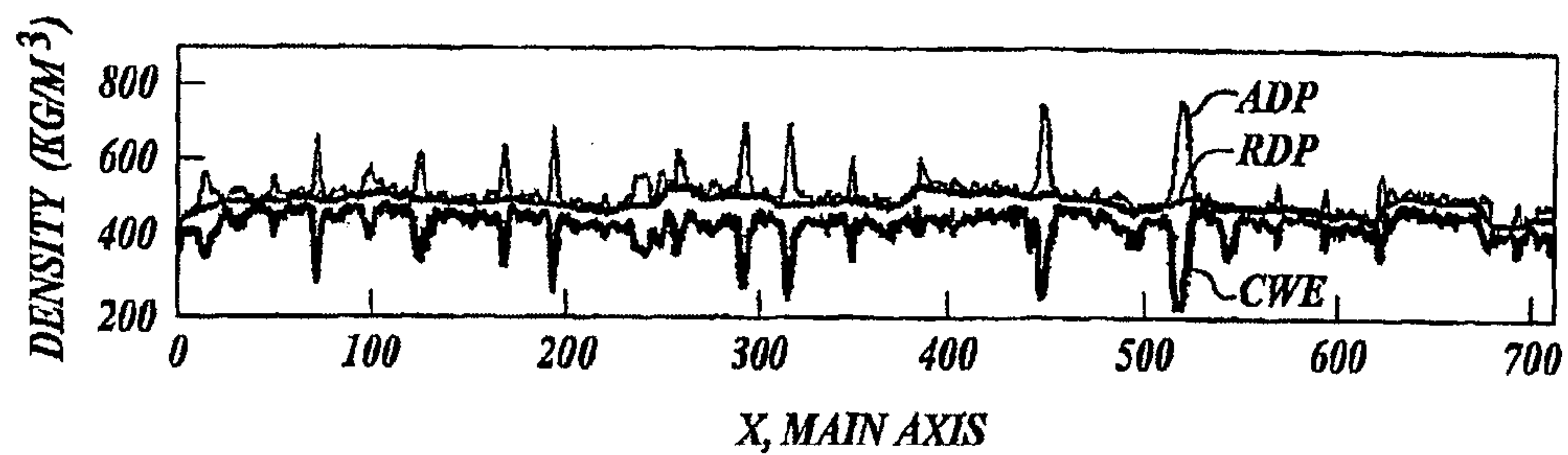
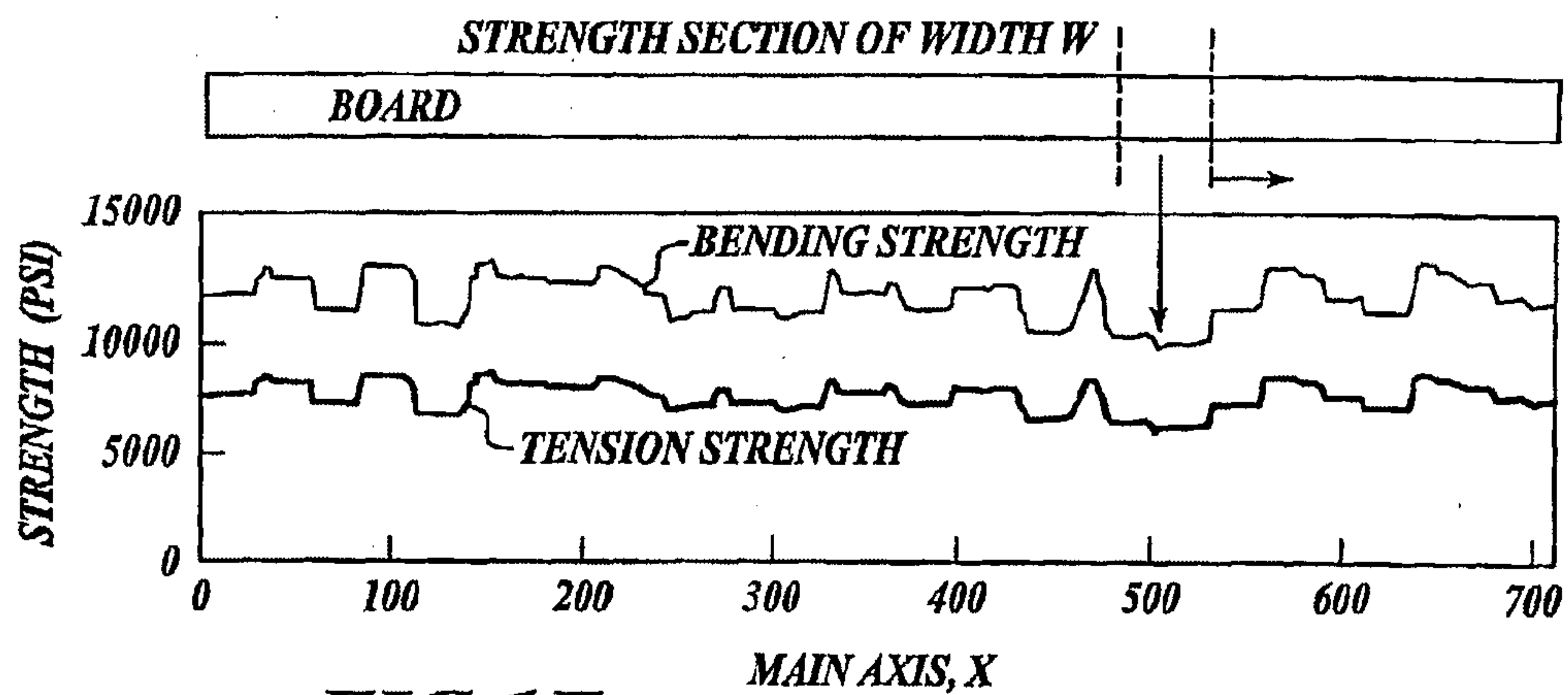
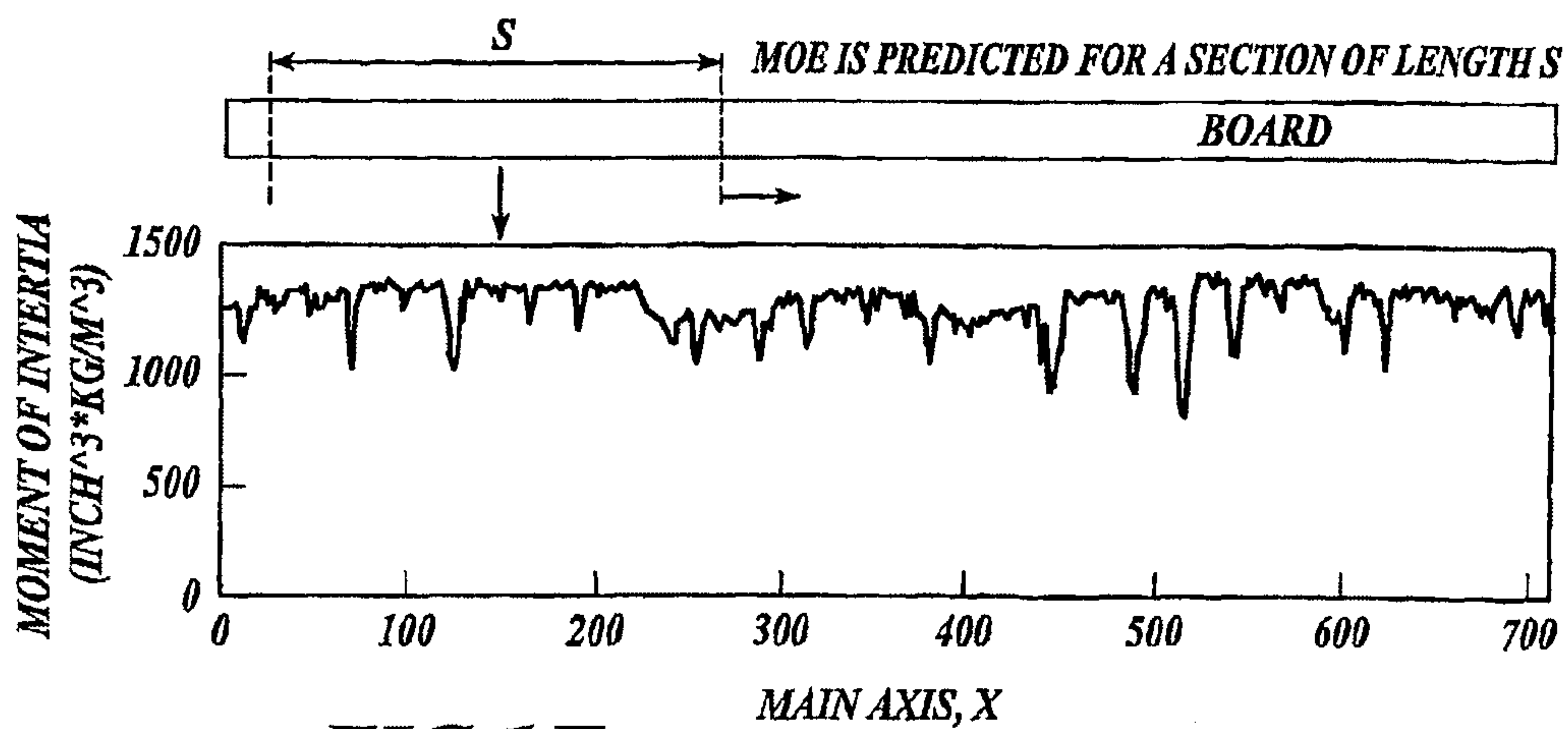
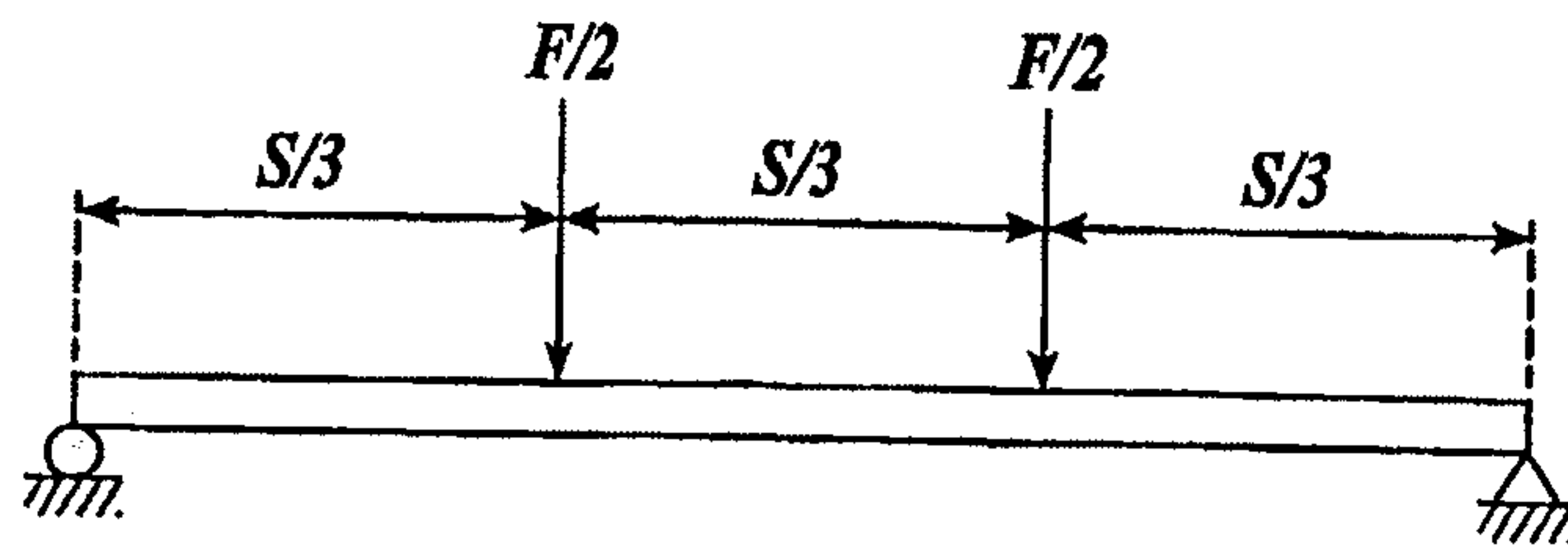
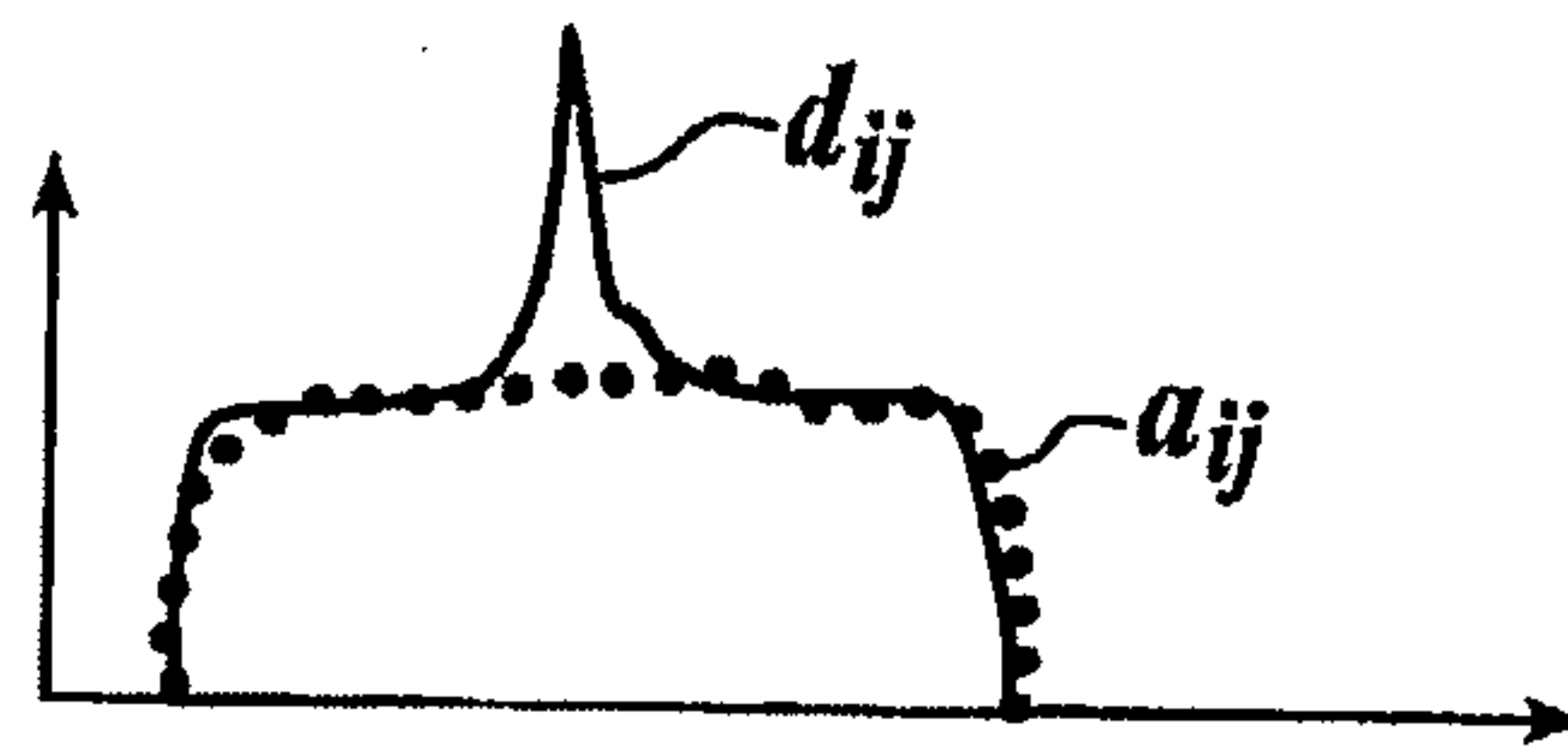
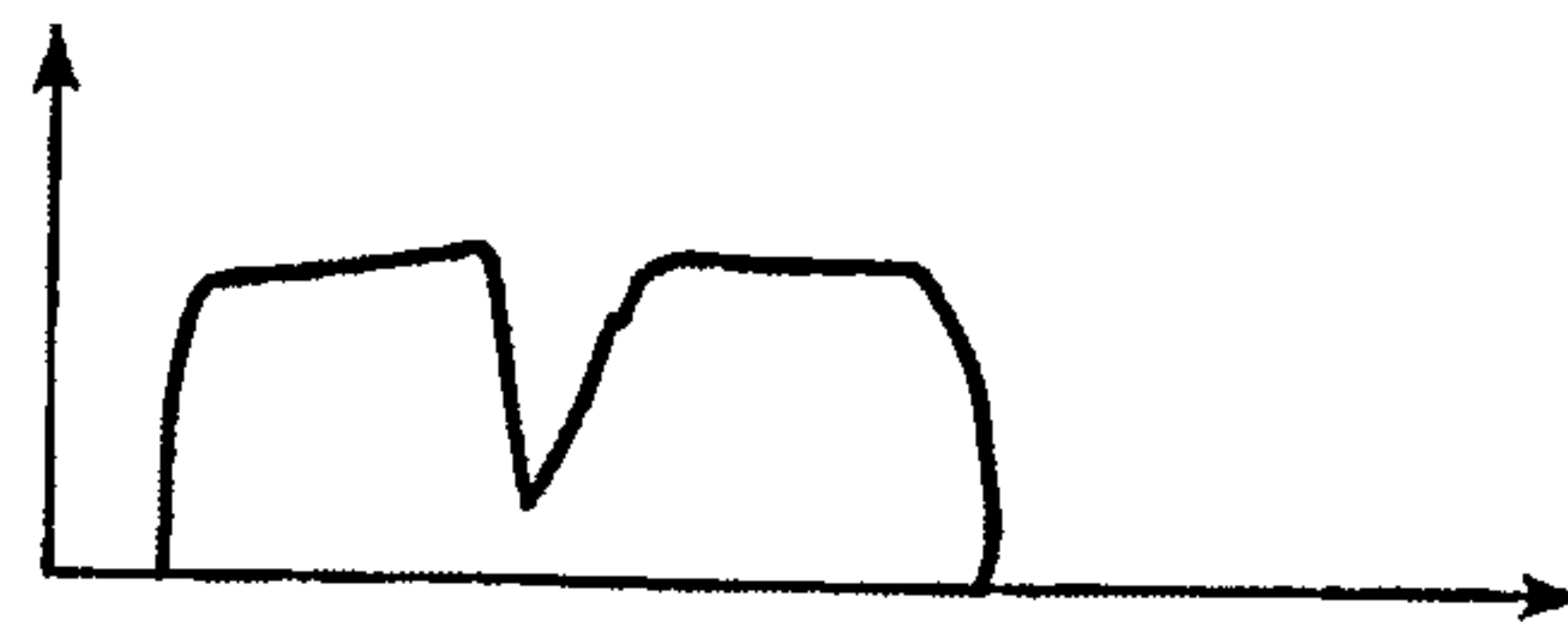


FIG.1C

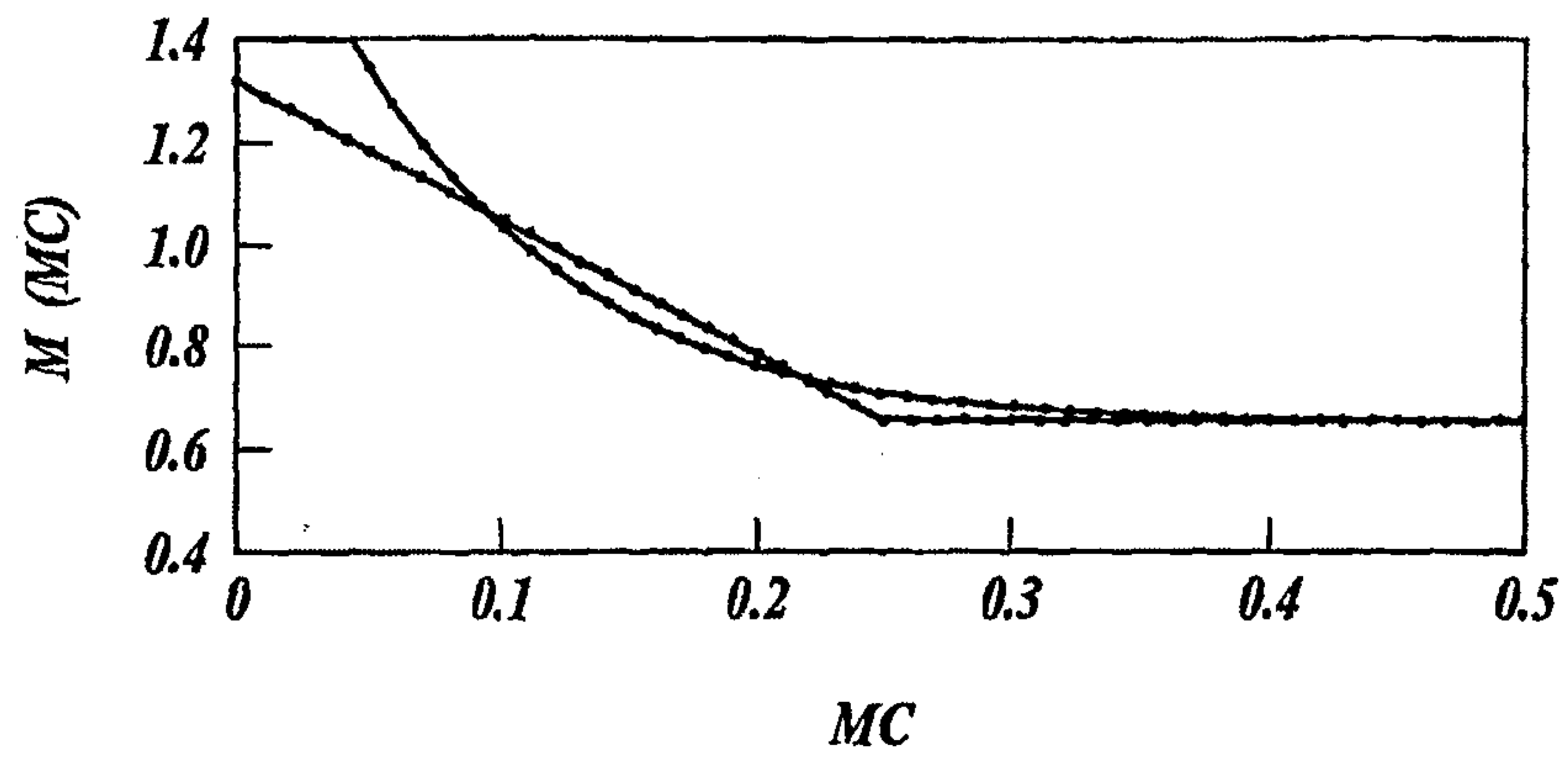
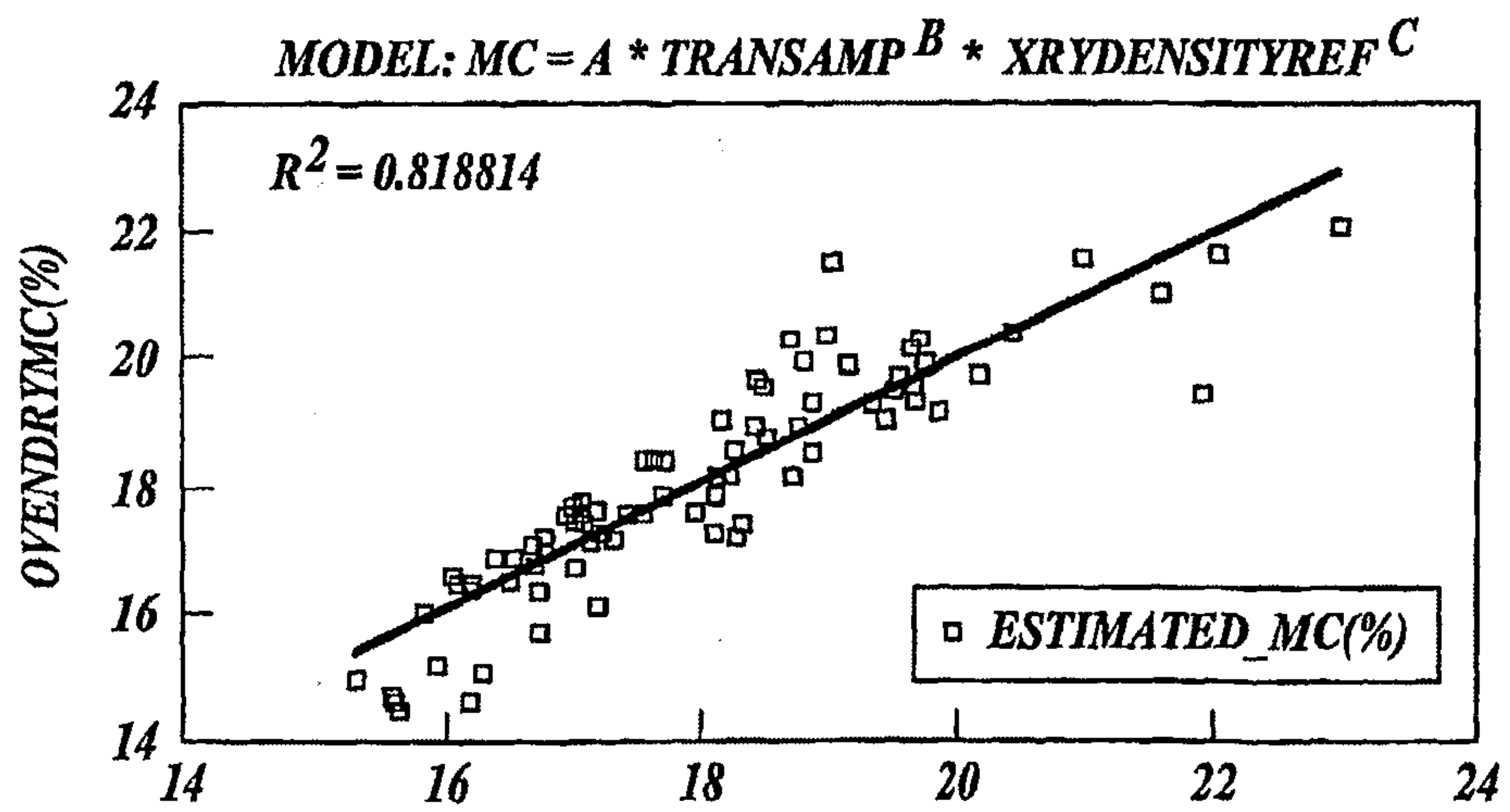
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**FIG. 1D****FIG. 1E****FIG. 1F**

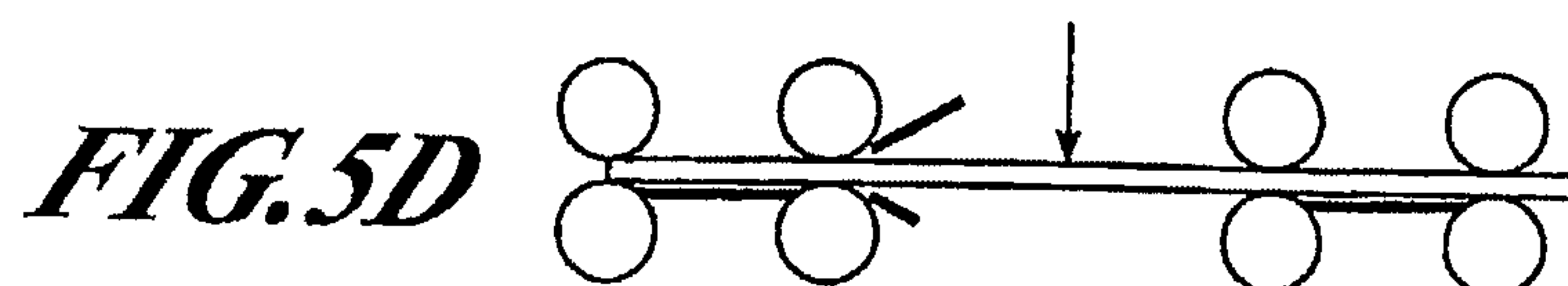
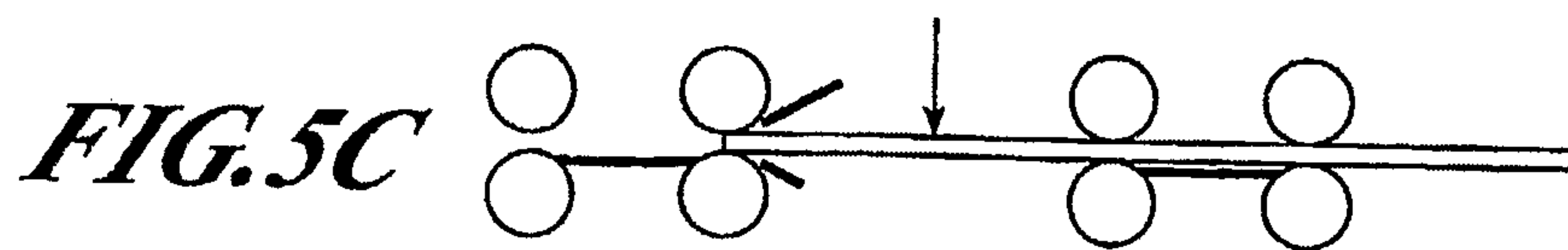
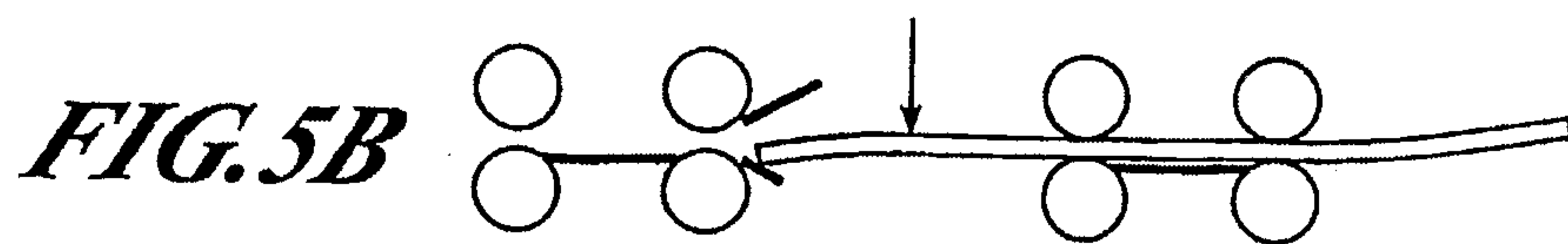
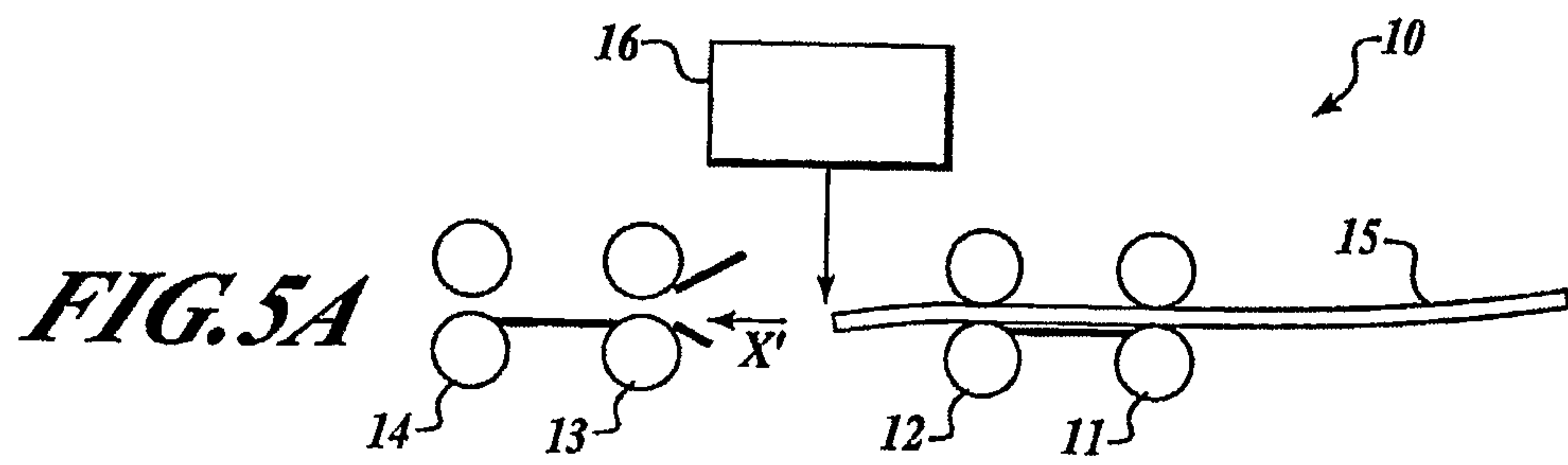
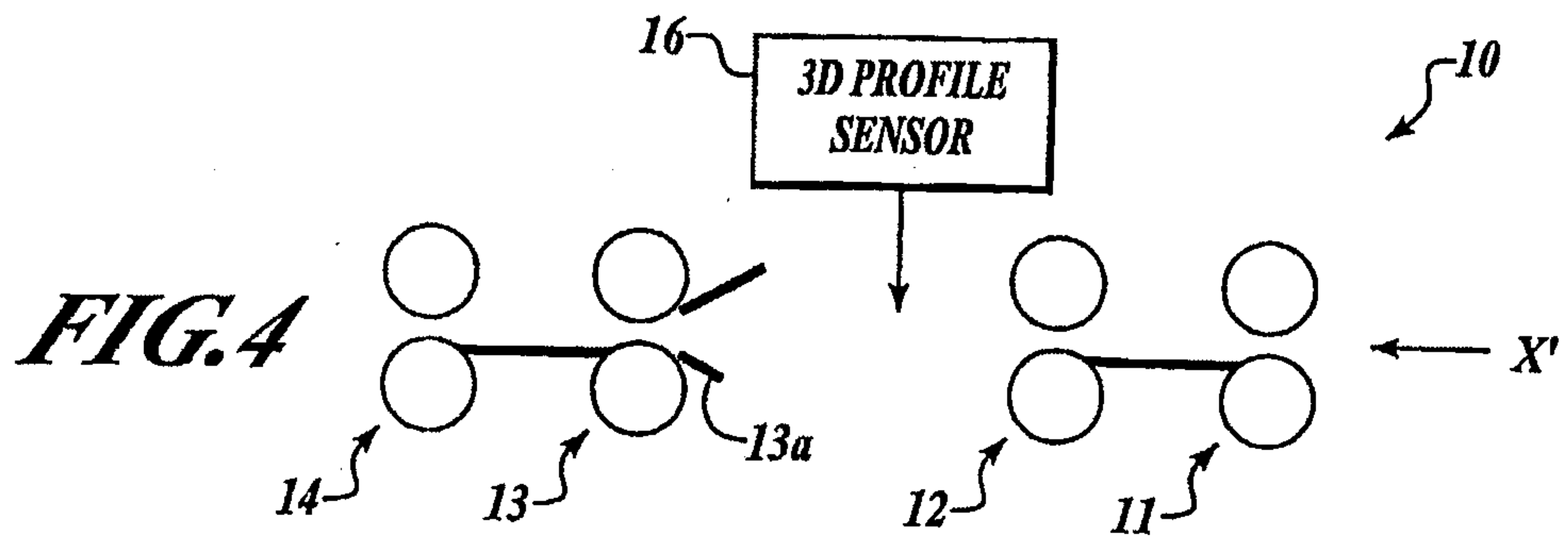
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**FIG.1G****FIG.2A****FIG.2B**

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**FIG.3****FIG.3A**

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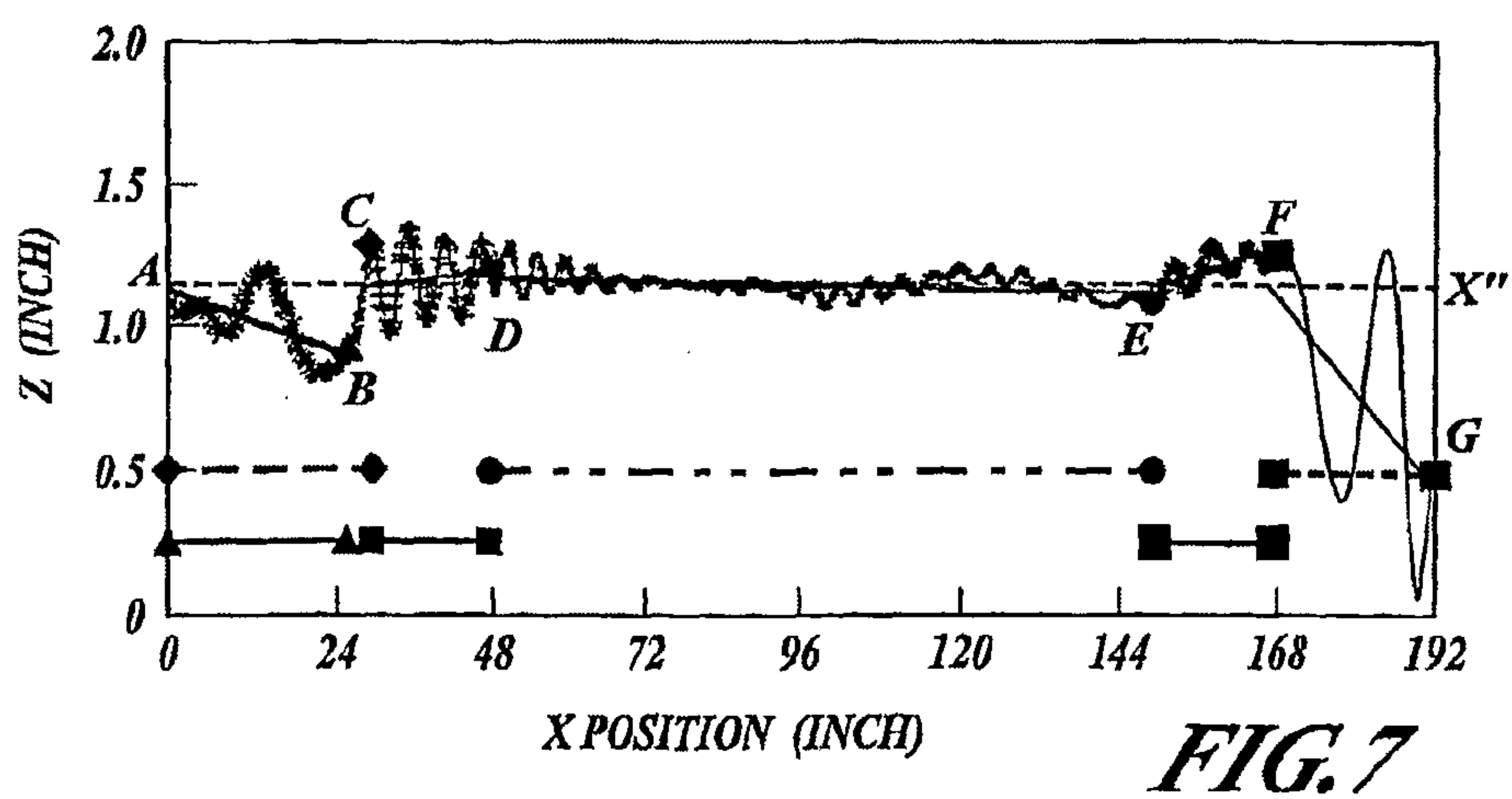
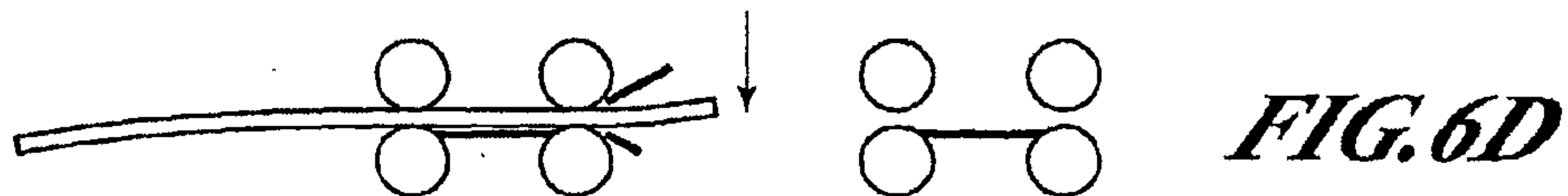
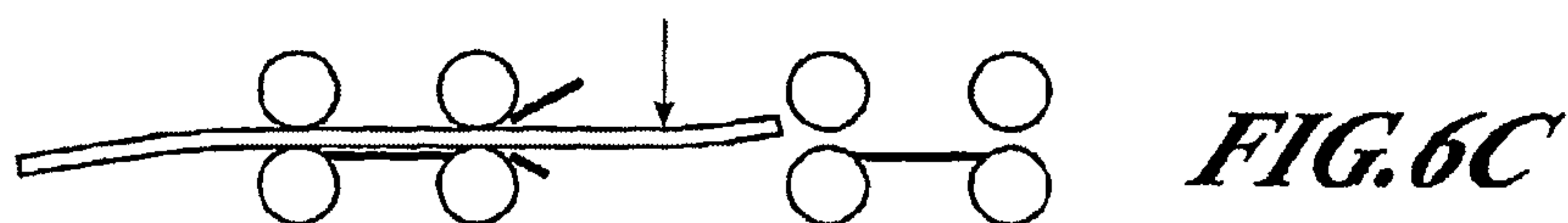
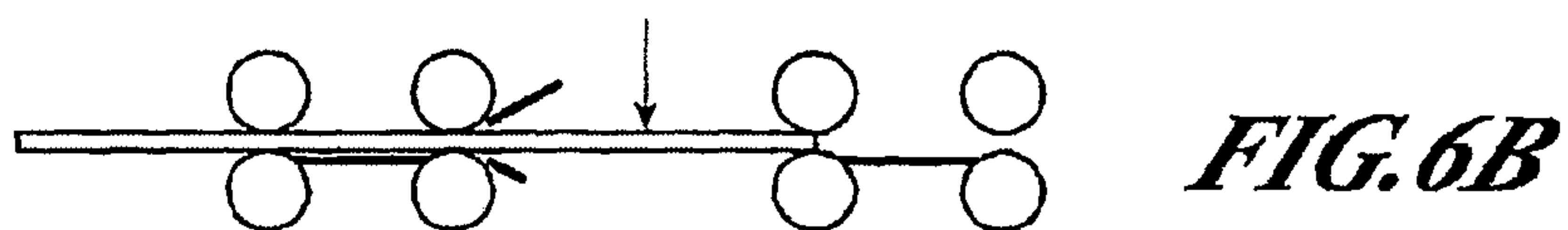
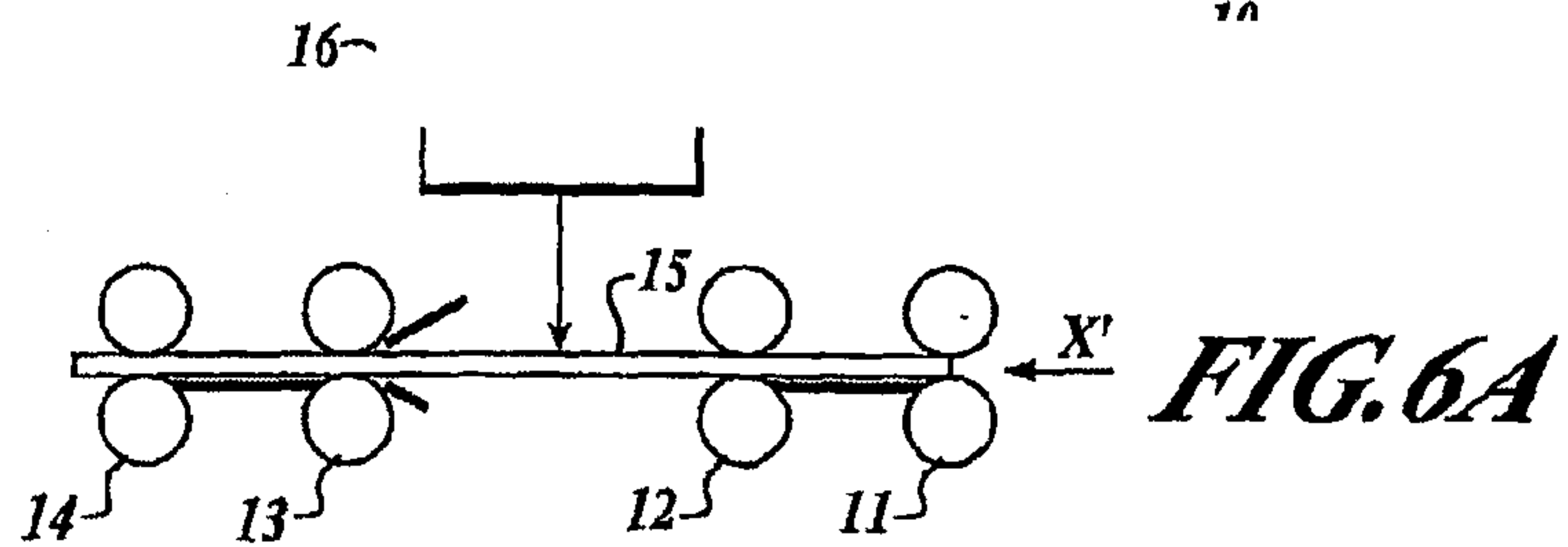


FIG. 7

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