DETERMINING THE STRESS PATTERN IN THE HH RAILROAD TIES DUE TO DYNAMIC LOADS[1]

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Abstract

This paper deals with the determination of the stress propagation in the HH10 type of steel railroad ties under dynamic loads.

The HH10 type of steel ties were tested for fatigue at the University of Illinois at Urbana-Champaign. Simultaneously with the laboratory fatigue tests, I was modelling the stress distribution in the tie due to the dynamic loads with using finite-element software 'ABAQUS'.

After the introduction, the laboratory arrangement of the tie fatigue test will described in Chapter 2. Chapter 3 details the steps in building up the finite-element model of the 'HH' railroad ties. In Chapter 4, the stress pattern and numerical values for the stresses and displacements of the tie due to dynamic loads as results of the finite-element program will be presented. The most important results will be summarized in Chapter 5.

Keywords: railroad ties, sleepers.

1. Introduction

In academic year 1998/1999 I stayed at the Department of Civil Engineering, University of Illinois at Urbana–Champaign, in the United States of America under Dr. Imre Korányi's scholarship. The purpose of my stay was to carry out a research in the field of railway engineering, with emphasis on railway tracks, that is related to my professional field of research towards the degree of PhD.

A railroad tie manufacturer company charged the University with testing the HH type of railroad steel ties for fatigue. I had the job to determine the stress pattern in the ties due to dynamic loads, by using finite-element method software 'ABAQUS'.

In this paper, I summarize the results and some intermediate steps of my research.

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[1]Summary of results of research, carried out at the University of Illinois at Urbana – Champaign, USA, in academic year 1998/99

2. Testing of the 'HH' Railroad Ties for Fatigue at the University of Illinois [1]

2.1. Description of the 'HH' Types of Railroad Ties

The HH types of railroad ties are manufactured of three different thickness, 10 mm, 12 mm and 14 mm. Their symbols are HH10, HH12 and HH14. The HH10 type of railroad tie is illustrated in *Fig. 2.1* modelled by the finite element software 'ABAQUS'.

The HH10 type of railroad ties that have a thickness of 10 mm is intended to be used in side tracks, industrial tracks, classification yards and in tracks with low speed limit. The HH12 ties are planned to be used on heavy-axle-load main lines; and the HH14 ties are planned for wide gauge railroad lines. Only the HH10 ties were tested for fatigue at the University of Illinois [4].

Fig. 2.2 indicates the cross-section of the HH10, HH12 and HH14 ties. It has been drawn based on the drawings of the manufacturer. Some sizes are intentionally missing [2].

The material of the tested ties is A36 steel according to the ASTM Standards.
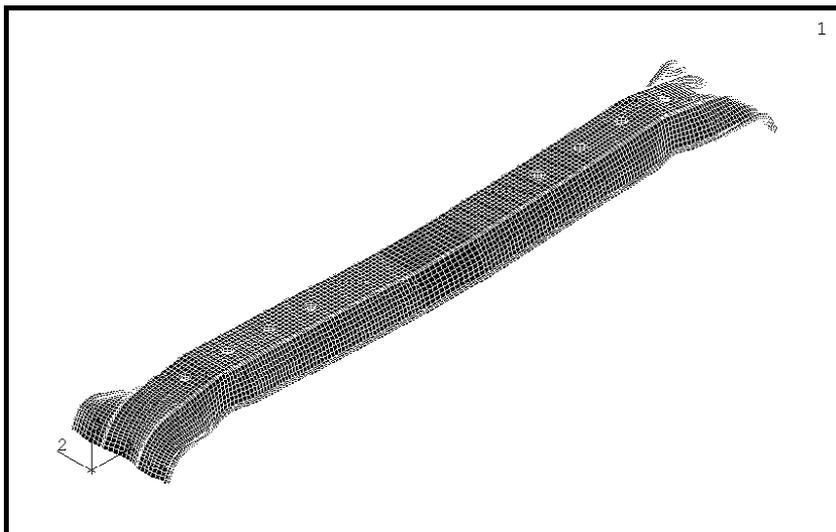
Fig. 2.1. The HH10 type of steel tie modeled by finite-element software ABAQUS

2.2. Laboratory Arrangement for the Tie Fatigue Test

The laboratory testing has the aim to investigate the fatigue limits of the railroad ties with the purpose to forecast the life cycle of the ties in specific railroad traffic
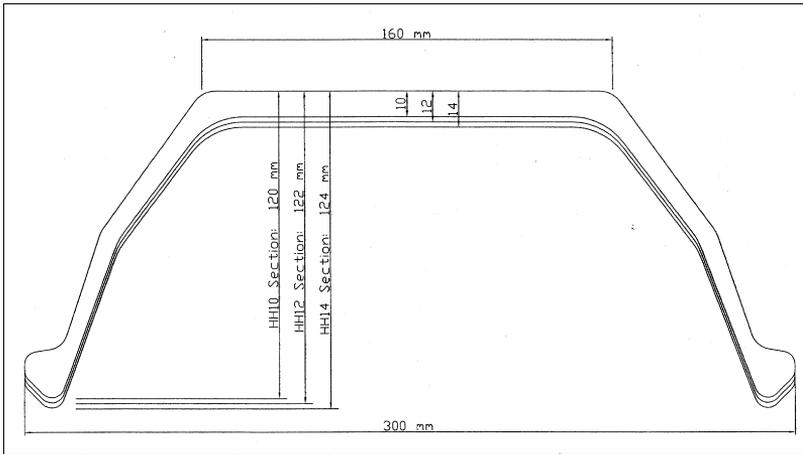
Fig. 2.2. Cross-section of the HH10, HH12 and HH14 ties. Some sizes are intentionally missing.

conditions, such as speed, axle load, etc.

The laboratory testing arrangement is illustrated in *Fig. 2.3*. A hydraulic cylinder loaded a horizontal, thick steel beam with very high inertia against bending. A loading head was joined with a rotating joint to both ends of the steel beam that were shaped to load the rails so that the load applied to the rails has the required angle and goes through the required point of the rail head (*Fig. 2.3*). The direction of the force loading the railhead had an angle of 21° to the vertical.

The rail fastening system is Pandrol. Elastic pads should be placed under the rail, between the rail and the tie, whose elasticity is minimum 150 kN/mm.

The ties are supported by rubber pads that should be placed so that the outer end of the rubber pads coincide with the inner end of the end spade rounding of the tie. The pads are 800 mm long and their width is equal to the width of the top surface of the tie. The thickness of the pads may not be more than 0.25 times the width. The compliance of the rubber pads should be in the range of $0.025 - 0.035$ mm/kN in case of the test frequency. The rubber pads are supported by steel pads whose surface is shaped the same way as the bottom surface of the top section of the tie.

2.3. Loads Applied to the Ties

The tie fatigue tests were carried out at a frequency of 3 Hz and 7 Hz. The shape of the dynamic load wave was sinusoidal.

The maximum value of the applied dynamic load was changed from series to series. Tests were carried out with the maximum load value of 200 kN, 220 kN,

235 kN, 250 kN, 280 kN and 300 kN as well. The minimum value of the dynamic load was 10 per cent of the maximum value. The maximum accuracy of the applied load is 2 per cent that means that the magnitude of the applied load may not deviate more than 2 per cent of its theoretical value at all times from the theoretical value.

The direction of the load had an angle of 21° to the vertical.

Fig. 2.3. Testing of the HH 10 steel tie for fatigue at the University of Illinois

2.4. Results of the Laboratory Tests

The laboratory tests for fatigue finish with either a run-out or a failure. A test finishes with a run-out if a crack longer than 3 mm cannot be observed by the Magnetic Particle Inspection after 5 millions of load repetition had been applied to the tie. The test should be terminated if a crack becomes visible on the surface of the tie before 5 millions of load repetition is applied. If a crack longer than 3 mm can be observed on the tie by the Magnetic Particle Inspection, the tie also fails the fatigue tests.

3. Steps in Building up the Finite-Element Model of the 'HH' Railroad Ties

3.1. Description of Finite-Element Computer Software 'ABAQUS' [3]

'ABAQUS' is a suite of powerful engineering simulation programs, based on the finite element method that can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations. ABAQUS contains an extensive library of elements that can model virtually any geometry. It has an equally extensive list of material models that can simulate the behaviour of most typical engineer materials including metals, rubber, polymers, composites, reinforced concrete, crushable and resilient foams, and geotechnical materials such as soils and rock. Designed as a general-purpose simulation tool, ABAQUS can be used to study more than just structural (stress/displacement) problems. It can simulate problems in such diverse areas as heat transfer, mass diffusion, thermal management of electrical components (coupled thermal-electrical analyses), acoustics, soil mechanics (coupled pore fluid-stress analyses), and piezoelectric analysis.

3.2. The Coordinate System

The ABAQUS models of the ties are fixed in a spatial, right-hand coordinate system. The '1' axis of the coordinate system is included by the longitudinal plane of symmetry and normal to the lateral plane of symmetry. The '2' axis of the coordinate system is included by the lateral plane of symmetry and normal to the longitudinal plane of symmetry. The '3' axis of the coordinate system is identical to the intersection line of the two planes of symmetry of the tie. The origin of the coordinate system is located so the '3' coordinate of the points top surface of the tie in the lateral plane of symmetry is equal to the height of the tie at that cross-section. *Fig. 2.1* shows the coordinate system and the model of the HH10 tie.

3.3. The Applied Mesh of the Tie

Fig. 2.1 illustrates the meshed model of the HH10 tie. The element library of ABAQUS offers several different types of elements. The sufficient element type is C3D20R that is 3 dimensional 20-node cubic brick element with reduced integration.

3.4. Material Properties

A test was made to measure the Young's modulus of the rubber pad. The material properties of the steel and the rubber pad defined in the model, are summarized in *Table 3.1*:

Table 3.1. Material properties of the steel and the rubber pad

Material	Material properties	
	Young's modulus	Poisson's ratio
Steel	$2.1 * 10^5$ N/mm^2	0.3
Rubber	6.9357 N/mm^2	0.3

3.5. Boundary Conditions

The ties are supported by rubber pads and the rubber pads are supported by steel pads whose surface is shaped the same way as the bottom surface of the top section of the tie. The support system is described in more details in Chapter 2.2. *Fig. 3.1* shows a quarter of the HH10 tie and the rubber pad.

The following boundary conditions are defined in the ABAQUS model:

- The bottom nodes of the rubber pads are fixed.
- The same nodes define the top surface of the rubber pads as those define the bottom surface of the tie.
- It has also been checked that it is enough to model half of the tie or quarter of the tie, with employing the necessary boundary conditions representing symmetry.

3.6. Definition of Loads

In the ABAQUS model, the loads are defined that were actually applied in the laboratory during the fatigue test. The shape of the dynamic load wave was sinusoidal. The maximum value of the axle load is 200 kN and 250 kN in the computations. The minimum value of the load is 10 per cent of its maximum value in all cases. Dynamic assessments were carried out with the frequency of the load of 3 Hz, 5 Hz, 7 Hz and 10 Hz.

Half of the axle load is applied to one rail. The direction of the load has an angle of 21° to the vertical. The loading system of the ties is described in Chapter 2.3.

In ABAQUS, these loads can be modelled by the following components:

- A uniformly distributed pressure perpendicular to the surface of the tie under the rail base;
- A triangularly distributed pressure perpendicular to the surface of the tie to model the bending moment;
- Nodal forces parallel to the surface of the tie to model the horizontal components of the applied load.
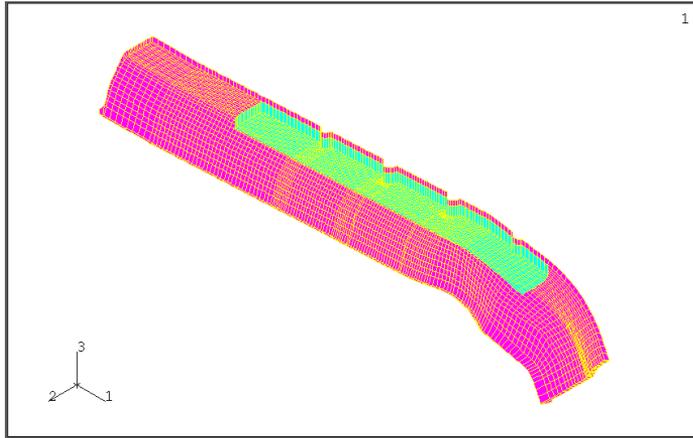
Fig. 3.1. A quarter of the tie (bottom view) and the rubber pad indicated in green

In the computations, the magnitude of the dynamic load is defined in a tabular form, ie. at discrete points of time in a cycle of loading. The load is defined at 16 time points within one cycle as illustrated in *Fig. 3.2*. The points on the curve indicate at which time points the load is defined. Previously it was checked at how many time points the load has to be defined in order to obtain sufficient accuracy in the calculations.

The elapsed time between two time points in which the load is defined is one time increment.
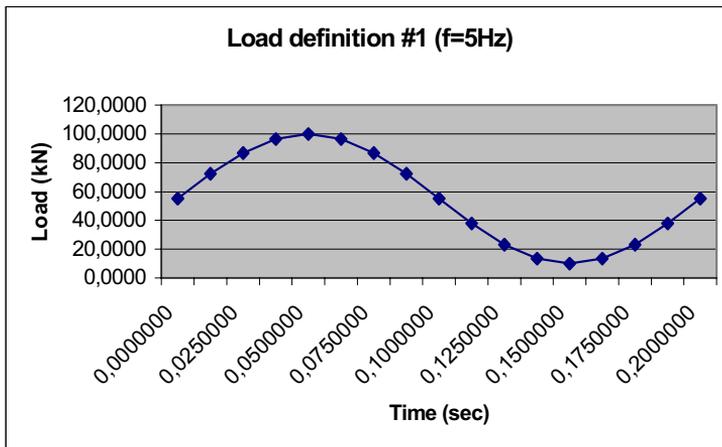
Fig. 3.2. Load definition

3.7. Node Numbering

Node 144001 and node 144201 have special importance in the results of the computations. *Fig. 3.3* indicates the location of the fastening hole and the ballast inspection wholes. *Fig. 3.4* shows the node numbering around the outer fastening whole.
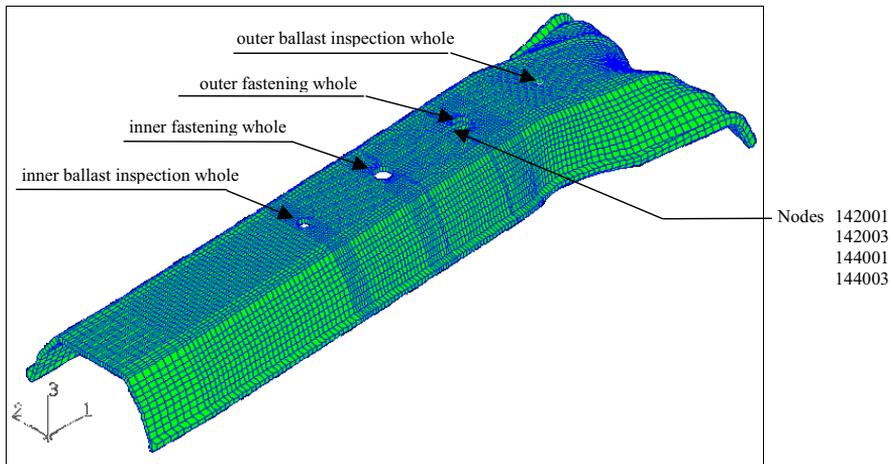
Fig. 3.3. Illustration of the node numbering on half of the tie
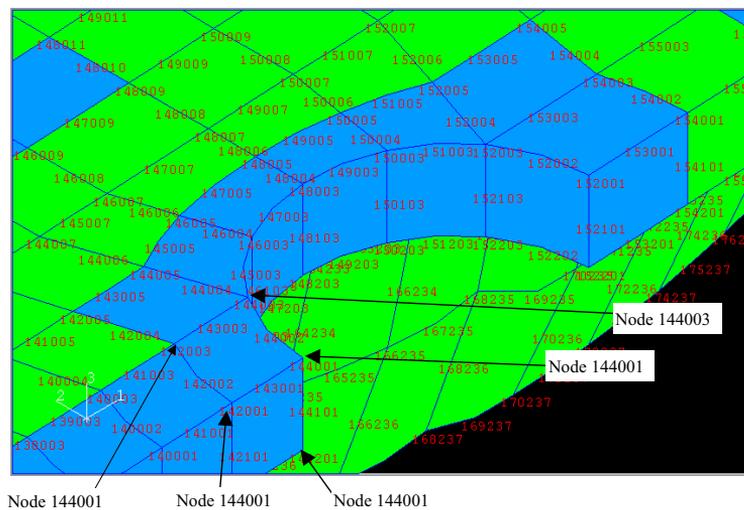
Fig. 3.4. Illustration of the node numbering around the *outer fastening hole*

3.8. Type of Analysis

All computations were made with linear elasticity and linear dynamics.

4. Dynamic Assessment of the HH10 Tie

Dynamic assessments of the HH10 tie have been carried out for the following axle loads and frequencies:

HH10 tie: 200 kN   3 Hz
           250 kN   3 Hz
           200 kN   5 Hz
           200 kN   7 Hz
           200 kN   10 Hz

4.1. Stress Response in the Tie due to Dynamic Load

4.1.1. Assessment of Response of Transverse Stress

The dynamic load applied to the tie with a frequency of 3 Hz is illustrated in *Fig. 4.1*. *Fig. 4.3* shows the load with a frequency of 7 Hz, and *Fig. 4.5* shows the load with a frequency of 10 Hz. The top magnitude of the load applied to one rail is 100 kN in all cases.

A comprehensive research has shown that it is the transverse normal stress (σ_{22}) – of the six stress components (longitudinal, lateral and vertical normal stress and the three shear stress components) – that has the highest values through the evaluation period.

The transverse normal stress reaches its maximum values in compression in node 144001 and in tension in node 144201. These nodes are located on the inner edge of the outer fastening whole, along the longitudinal plane of symmetry. Node 144001 is on top surface, node 144201 is on the bottom surface. For illustration, please see *Fig. 3.3 – 3.4* and *4.7 – 4.10*.

The response – the magnitude of the transverse normal-stress in element 142001 is illustrated in *Fig. 4.2* in case when the frequency of the load is 3 Hz, in *Fig. 4.4* in case when the frequency of the load is 7 Hz, and in *Fig. 4.6* when the frequency of the load is 10 Hz. Nodes 144001 and 144201 are nodes of element 142001.

Frequency: f= 3 Hz
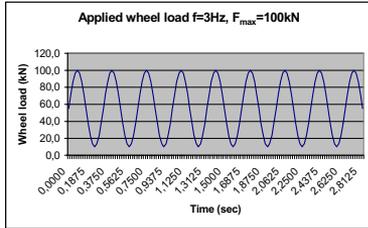
Fig. 4.1. The applied wheel load in function of time (frequency of 3 Hz)

Frequency: f= 7 Hz
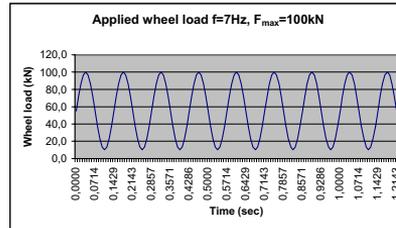
Fig. 4.3. The applied wheel load in function of time (frequency of 7 Hz)

Frequency: f= 10 Hz
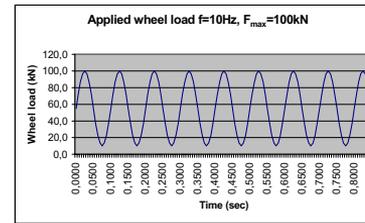
Fig. 4.5. The applied wheel load in function of time (frequency of 10 Hz)
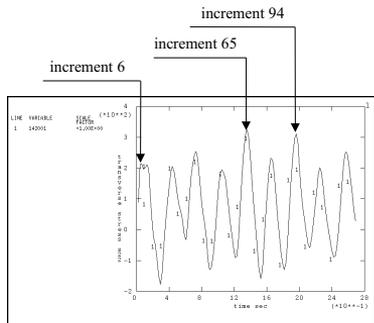
Fig. 4.2. The transverse normal-stress (σ_{22}) in respect of time in element 142001 ($f = 3$ Hz)
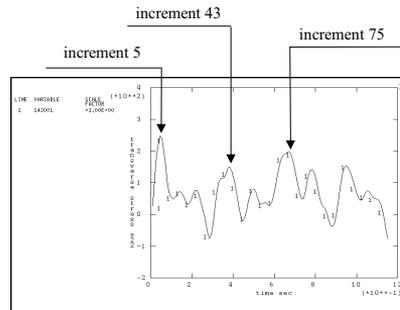
Fig. 4.4. The transverse normal-stress (σ_{22}) in respect of time in element 142001 ($f = 7$ Hz)
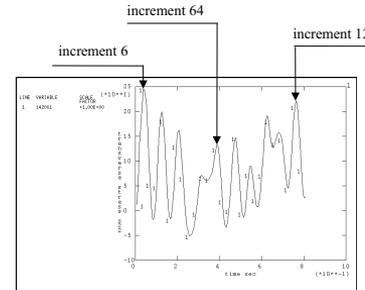
Fig. 4.6. The transverse normal-stress (σ_{22}) in respect of time in element 142001 ($f = 10$ Hz)

Table 4.1 shows the absolute maximum and some of the local maximum values of the transverse stress in function of time in the HH10 tie loaded by an axle load of 200 kN with frequencies of 3 Hz, 7 Hz and 10 Hz. All maximum values of the transverse normal stress in compression (shown in *Table 4.1*) arise in node 144001 and in tension in node 144201. Values marked with 'absolute maximum' are the absolute maximum values of the transverse stress through the entire evaluation period. The time increments are illustrated in *Figs. 4.2, 4.4*, and *4.6*.

Table 4.1. Absolute maximum and some of the local maximum values of the transverse stress (σ_{22}), in function of time

Frequency of load	The number of increment	Total accumulated time [seconds]	Maximum of σ_{22} for compression in the tie [MPa] (in node 144001)	Maximum of σ_{22} for tension in the tie [MPa] (in node 144201)	Remark
3 Hz	6	0.125	586.7	−569.5	local maximum
	35	0.729	649.5	−566.5	local maximum
	65	1.35	821.1	−707.7	**absolute max.**
	94	1.96	780.9	−694.1	local maximum
7 Hz	5	0.04464	690.7	−733.9	**absolute max**
	26	0.232	218.8	−260.3	local maximum
	43	0.384	399.2	−380.9	local maximum
	75	0.670	516.7	−467.5	local maximum
10 Hz	6	0.0375	686.0	−731.3	**absolute max.**
	19	0.119	517.4	−589.2	local maximum
	64	0.400	302.1	−408.8	local maximum
	122	0.762	612.6	−599.7	local maximum

4.1.2. Assessment of Response of Longitudinal and Vertical Stresses

For the *HH10 tie* loaded by an *axle load of 200 kN* with a *frequency of 3 Hz, Table 4.2* indicates the values of the transverse stress (σ_{22}), the longitudinal stress (σ_{11}), and the vertical stress (σ_{33}) in *node 144001* in the same time-increments as in *Table 4.1* in case of a frequency of 3 Hz. *Table 4.3* indicates the values of the transverse stress (σ_{22}), the longitudinal stress (σ_{11}), the vertical stress (σ_{33}) in *node 144201* in the same time increments as those in *Table 4.1* in case of a frequency of 3 Hz.

Tables *4.2* and *4.3* show that the longitudinal and the vertical normal stress have a low value at nodes 144001 and 144201 in time increments when the transverse stress reaches its maximum.

Comprehensive computations also prove that transverse, longitudinal and the vertical stress components reach their maximum values at different locations in the tie and in different time increments.

Table 4.2. Values of the transverse (σ_{22}), longitudinal (σ_{11}) and vertical (σ_{33}) stresses at node 144001 in the same time increments as in *Table 4.1* in case of a frequency of 3 Hz

The number of increment	Total accumulated time (seconds)	Value of stress in node 144001 ($f = 3$ Hz)		
		σ_{22} [MPa]	σ_{11} [MPa]	σ_{33} [MPa]
6	0.125	-569.5	12.83	1.583
35	0.729	-566.5	6.401	2.938
65	1.35	-707.7	6.463	4.258
94	1.96	-694.1	5.415	4.026

Table 4.3. Values of the transverse (σ_{22}), longitudinal (σ_{11}) and vertical (σ_{33}) stresses at node 144201 in the same time increments as in *Table 4.1* in case of a frequency of 3 Hz

The number of increment	Total accumulated time (seconds)	Value of stress in node 144201 ($f = 3$ Hz)		
		σ_{22} [MPa]	σ_{11} [MPa]	σ_{33} [MPa]
6	0.125	586.7	-4.094	-8.062
35	0.729	649.5	-2.888	-8.098
65	1.35	821.1	-2.855	-9.811
94	1.96	780.9	-4.498	-9.587

4.1.3. *Effect of Frequency of Load on Frequency of Response of Stress*

Based on the results of the computations and on *Figs. 4.1 – 4.6* it can be concluded that there is no correlation between the frequency of the load and the frequency of the response. The magnitude of the stresses in function of time is not periodic, the frequency of the response is not equal to the frequency of the load.

4.1.4. *Effect of Frequency of Load on Magnitude of Response of Stress*

Based on the results of comprehensive computations and on the values of *Table 4.1* it can be concluded that there is no correlation between the frequency of the load and the maximum values of the stresses. With increasing the frequency of the load, the maximum values of the stresses neither strictly increase nor strictly decrease.

4.1.5. Effect of Magnitude of Load on the Responses

Based on the computations, it can be concluded that when linear dynamics are used, if the load is increased by a factor, all stress, strain and displacements responses will increase by the same factor in the tie. Increasing the magnitude of the load will not modify the frequency of the response.

4.2. Distribution of the Transverse Stress in the Tie

4.2.1. Distribution of the Transverse Stress in the Tie due to Dynamic Load with a Frequency of 3 Hz

In case when the HH10 tie is loaded by an axle load of 200 kN with a frequency of 3 Hz, the transverse normal stress, σ_{22}, *reaches its absolute maximum value in increment 65* during the total time period of the assessment. It is *707.7 MPa for compression* and this value arises on the top surface of the tie, on the inner side of the outer fastening whole where the longitudinal plane of symmetry intersects the whole. The number of this node is 144001 and the element number is 142001. The absolute *maximum value of the transverse normal stress in tension is 821.1 MPa* and this value arises on the bottom surface of the tie, on the inner side of the outer fastening whole where the longitudinal plane of symmetry intersects the whole. The number of this node is 144201 and the element number is 142001. Node numbering is illustrated in *Fig. 3.4*.

Fig. *4.7* shows the pattern of the transverse stress on the top surface of the tie in increment 65. in case of an axle load of 200 kN with a frequency of 3 Hz, and *Fig. 4.8* indicates the transverse stress on the bottom surface. The same pattern of transverse stress is obtained in increments 2, 6, 21, 35, 65, 94 and in increments when the transverse stress reaches its absolute maximum value or a local maximum value in function of time that is close to the absolute maximum.

Figs. *4.7* and *4.8* indicate that the high stress concentrations on the inner side of the outer fastening whole decrease rapidly on the surface of the tie as the distance increases from the whole. *Table 4.4* summarizes the values of the transverse stress (σ_{22}) at nodes 142001, 142003, 144001, 144003 and also contains the distance of these nodes from node 144001. These nodes are on the top surface of the tie. *Table 4.5* summarizes the values of the transverse stress (σ_{22}) at nodes 142201, 142203, 144201, 144203 and also contains the distance of these nodes from node 144201. These nodes are on the bottom surface of the tie.

Tables *4.4* and *4.5* indicate that the stress values decrease down to 57.4% to 68.0% of the maximum value over a distance 8.9 to 10.5 mm. Therefore, high stress peaks arise only in a little, concentrated area.
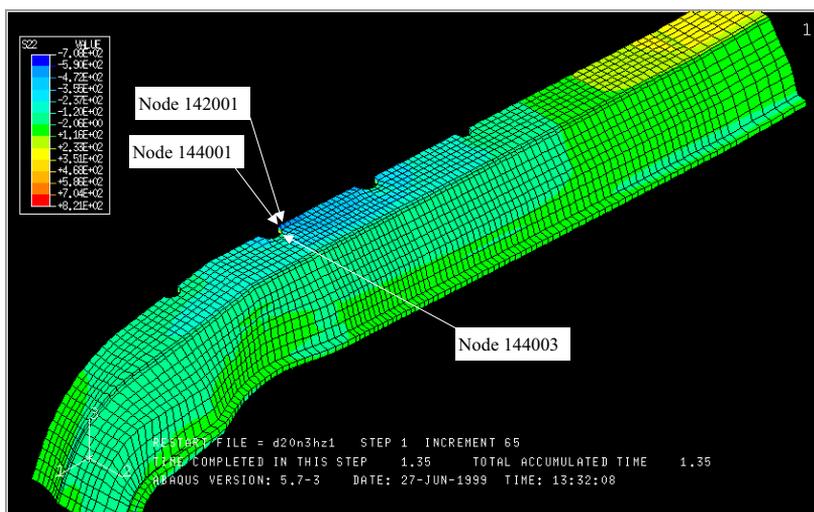
Fig. 4.7. Pattern of the transverse stress (σ_{22}) on top surface of the HH10 tie loaded by an axle load of 200 kN with a frequency of 3 Hz. Increment: 65, total accumulated time: 1.35 sec. Maximum value of the transverse stress: 821 MPa for tension; 708 MPa for compression.

Table 4.4. The values of the transverse stress (σ_{22}) at nodes 142001, 142003, 144001, 144003 in increment 65 and the distance of these nodes from node 144001

Node number	Value of transverse stress σ_{22} [Mpa] in increment 65	Distance of node from node 144001 [mm]
144001	-707.7	0.00
144003	-427.9	10.45
142001	-534.2	8.88
142003	-494.8	11.78

4.2.2. *Distribution of the Transverse Stress in the Tie Due to Dynamic Load with a Frequency of 7 Hz*

In case when the HH10 tie is loaded by an axle load of 200 kN with a frequency of 7 Hz, the transverse normal stress, σ_{22}, *reaches its absolute maximum value* in *increment 5* during the total time period of the assessment. It is *733.9 MPa for compression* and this value arises on the top surface of the tie, on the inner side of the outer fastening whole where the longitudinal plane of symmetry intersects the whole (element number 142001, node number: 144001). The absolute *maximum value of*
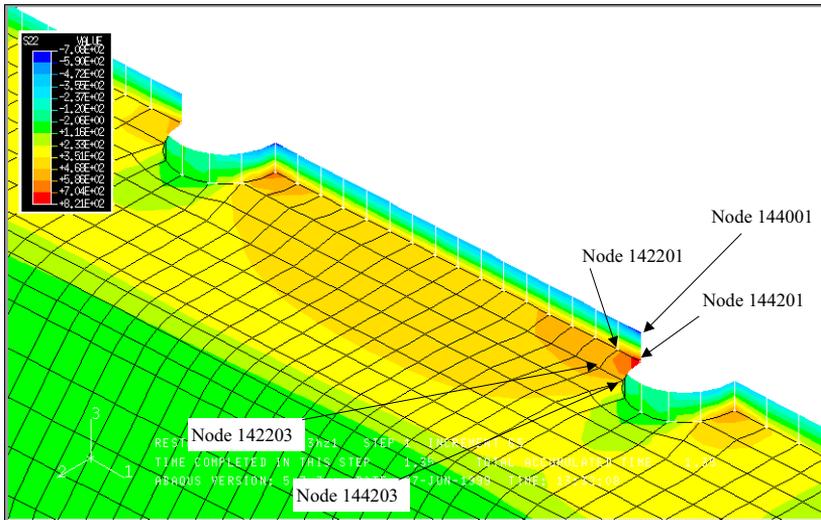
Fig. 4.8. Pattern of the transverse stress (σ_{22}) on bottom surface of the HH10 tie loaded by an axle load of 200 kN with a frequency of 3 Hz. Increment: 65, total accumulated time: 1.35 sec. Maximum value of the transverse stress: 821 MPa for tension; 708 MPa for compression.

Table 4.5. The values of the transverse stress (σ_{22}) at nodes 142201, 142203, 144201, 144203 in increment 65 and the distance of these nodes from node 144201

Node number	Value of transverse stress σ_{22} [Mpa] in increment 65	Distance of node from node 144201 [mm]
144201	821.1	0.00
144203	471.9	10.45
142201	558.7	8.88
142203	531.6	11.78

the transverse normal stress in tension 690.7 MPa arises on the bottom surface of the tie, on the inner side of the outer fastening whole where the longitudinal plane of symmetry intersects the whole (element number 142001, node number: 144201).

The *transverse stress* also reaches a high value in *increment 75*. This is a local maximum that is close to the absolute maximum. The value of the stress is *516.7 MPa* for tension in node 144201 and it is *467.5 MPa* for compression in node 144001. The same stress pattern is obtained in increment 5, 75 and in increments when the transverse stress reaches its absolute maximum value or a local maximum

value in function of time that is close to the absolute maximum.
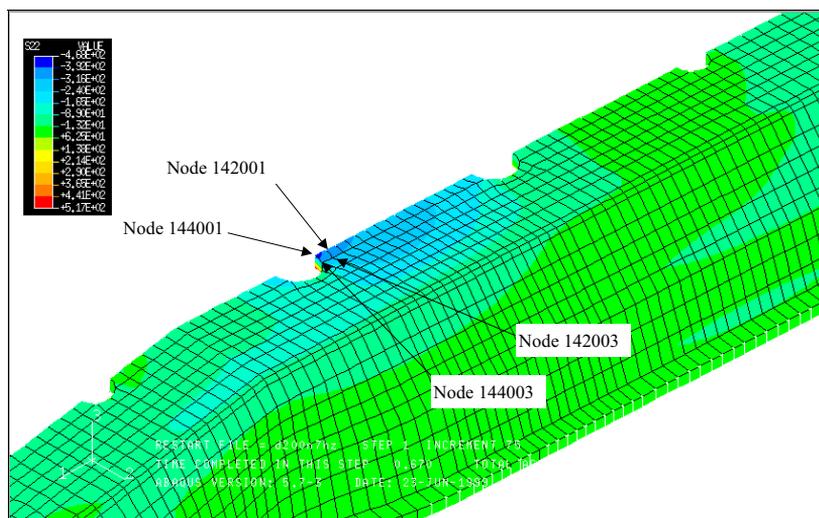
Fig. 4.9. Pattern of the transverse stress (σ_{22}) on top surface of the HH10 tie loaded by an axle load of 200 kN with a frequency of 7 Hz. Increment: 75, total accumulated time: 0.670 sec. Maximum value of the transverse stress: 517 MPa for tension; 468 MPa for compression.

Fig. 4.9 shows the pattern of the transverse stress on top surface of the tie in increment 75 in case when the tie is loaded by an axle load of 200 kN with a frequency of 7 Hz.

Fig. 4.9 indicates that the high stress concentrations on the inner side of the outer fastening whole decrease rapidly on the surface of the tie as the distance increases from the whole. *Table 4.6* summarizes the values of the transverse stress (σ_{22}) at nodes 142001, 142003, 144001, 144003 in increment 75 and also contains the distance of these nodes from node 144001. These nodes are on the top surface of the tie. *Table 4.7* summarizes the values of the transverse stress (σ_{22}) at nodes 142201, 142203, 144201, 144203 and also contains the distance of these nodes from node 144201. These nodes are on the bottom surface of the tie.

Tables 4.6 and *4.7* indicate that the stress values decrease down to 65.5% to 68.8% of the maximum value over a distance 8.9 to 10.5 millimeters. Therefore, high stress peaks arise only in a little, concentrated area.

4.2.3. Distribution of the Transverse Stress in the Tie Due to Dynamic Load with a Frequency of 10 Hz

In case when the HH10 tie is loaded by an axle load of 200 kN with a frequency

Table 4.6. The values of the transverse stress (σ_{22}) at nodes 142001, 142003, 144001, 144003 in increment 75 and the distance of these nodes from node 144001

Node number	Value of transverse stress σ_{22} [Mpa] in increment 75	Distance of node from node 144001 [mm]
144001	−467.5	0.00
144003	−316.6	10.45
142001	−354.9	8.88
142003	−324.1	11.78

Table 4.7. The values of the transverse stress (σ_{22}) at nodes 142201, 142203, 144201, 144203 in increment 75 and the distance of these nodes from node 144201

Node number	Value of transverse stress σ_{22} [Mpa] in increment 75	Distance of node from node 144201 [mm]
144201	516.7	0.00
144203	338.5	10.45
142201	352.6	8.88
142203	330.0	11.78

of 10 Hz, the transverse normal stress, σ_{22}, reaches its absolute *maximum value in increment 6* during the total time period of the assessment. It is *686.0 MPa in tension* and this value arises on the bottom surface of the tie, on the inner side of the outer fastening whole where the longitudinal plane of symmetry intersects the whole (node number 144201, element number 142001). The absolute *maximum value of the transverse normal stress in compression is 731.3 MPa* and this value arises on the top surface of the tie, on the inner side of the outer fastening whole where the longitudinal plane of symmetry intersects the whole (node number 144001, element number 142001).

The *transverse stress* also reaches a very high value, a local maximum in function of time that is close to the absolute maximum, in *increment 122*. The value of the stress is *612.6 MPa in tension* (node number 144201) and *599.7 MPa in compression* (node number 144001). The same stress pattern is obtained in increments 6, 122 and in increments when the transverse stress reaches its absolute maximum value or a local maximum value in function of time that is close to the absolute maximum.

When the HH10 tie is loaded by an axle load of 200 kN with a frequency of 10 Hz, the total accumulated time until increment 6 is 0.0375 seconds and until increment 122 it is 0.762 seconds. The total accumulated time until increment 6 is

too short, it is not enough for the dynamic waves to propagate and to be generated due to the initial inertia of the tie. Therefore, the values that should be considered as maximum values of the transverse normal stress is *612.6 MPa* in tension (node number 144201) and *599.7 MPa* in compression (node number 144001).

Fig. *4.10* shows the pattern of the transverse stress on bottom surface of the tie in increment 122 in case of an axle load of 200 kN with a frequency of 10 Hz.
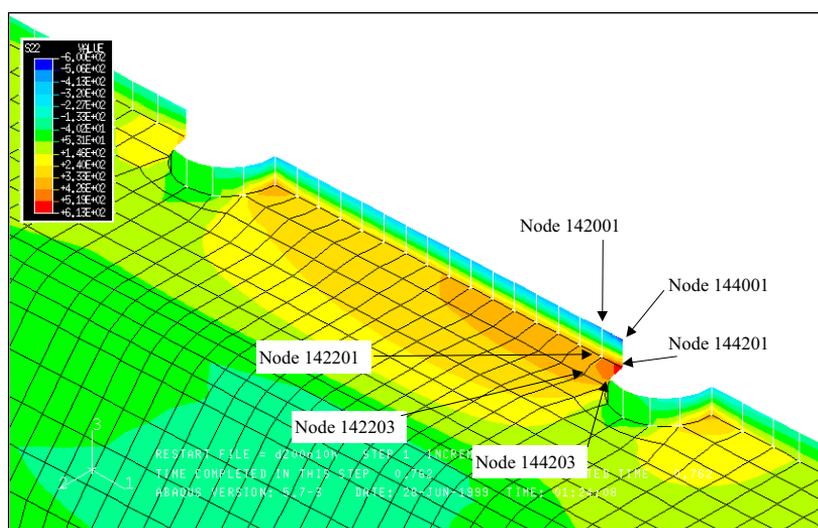
Fig. *4.10.* Pattern of the transverse stress (σ_{22}) on bottom surface of the HH10 tie loaded by an axle load of 200 kN with a frequency of 10 Hz. Increment: 122, total accumulated time: 0.762 sec. Maximum value of the transverse stress: 613 MPa for tension; 600 MPa for compression.

Fig. *4.10* indicates that the high stress concentrations on the inner side of the outer fastening whole decrease rapidly on the surface of the tie as the distance increases from the whole. *Table 4.8* summarizes the values of the transverse stress (σ_{22}) at nodes 142001, 142003, 144001, 144003 in increment 122 and also contains the distance of these nodes from node 144001. These nodes are on the top surface of the tie. *Table 4.9* summarizes the values of the transverse stress (σ_{22}) at nodes 142201, 142203, 144201, 144203 and also contains the distance of these nodes from node 144201. These nodes are on the bottom surface of the tie.

Tables 4.8 and *4.9* indicate that the stress values decrease down to 52.4% to 67.5% of the maximum value over a distance 8.9 to 10.5 millimeters. Therefore, high stress peaks arise only in a little, concentrated area.

Table 4.8. The values of the transverse stress (σ_{22}) at nodes 142001, 142003, 144001, 144003 in increment 122 and the distance of these nodes from node 144001

Node number	Value of transverse stress σ_{22} [Mpa] in increment 122	Distance of node from node 144001 [mm]
144001	−599.7	0.00
144003	−362.0	10.45
142001	−463.0	8.88
142003	−415.1	11.78

Table 4.9. The values of the transverse stress (σ_{22}) at nodes 142201, 142203, 144201, 144203 in increment 122 and the distance of these nodes from node 144201

Node number	Value of transverse stress σ_{22} [Mpa] in increment 122	Distance of node from node 144201 [mm]
144201	612.6	0.00
144203	327.6	10.45
142201	413.5	8.88
142203	384.1	11.78

4.3. Distribution of the Longitudinal Normal Stress, the Vertical Normal Stress, and Shear Stress Components in the Tie Due to Dynamic Load

The absolute maximum value of the longitudinal stress σ_{11} (S11) *is less than the half of that of the transverse stress.*

The absolute maximum value of the longitudinal normal-stress or a local maximum that is close to the absolute one may occur at either of two pairs of locations. One pair of location is on the edge of the outer fastening whole at the end of the radii perpendicular to the longitudinal plane of symmetry or on the outermost edge of the side of the tie. Where the transverse stress reaches its maximum value, the longitudinal stress has a neutral value and where the longitudinal stress reaches its maximum value, the transverse stress has a low value.

Fig. 4.11 indicates the *longitudinal stress* on top surface of the HH10 tie loaded by an axle load of 200 kN with a frequency of 3 Hz in increment 65.

The *vertical normal stress* (σ_{33}) is in a neutral state on the top section of the tie in the regions where the transverse and the longitudinal stresses reach their maximum values.

Shear stress components have very low values in the points where the transverse and the longitudinal stresses reach their maximum values.
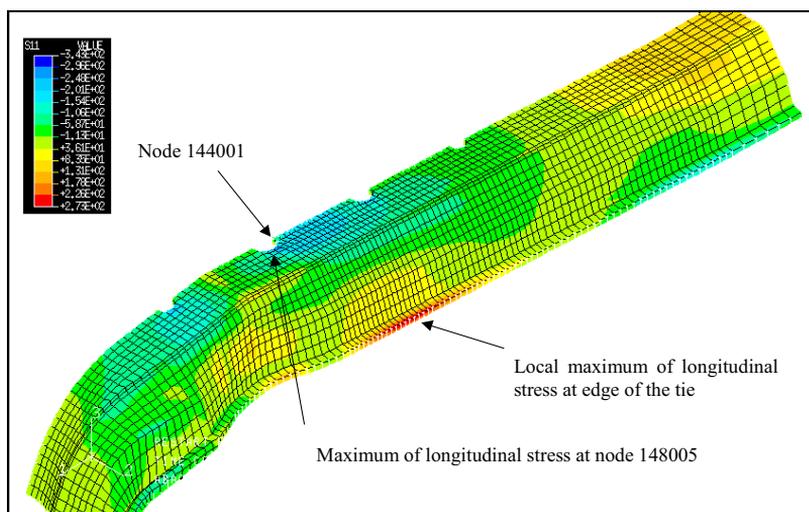
Fig. 4.11. Pattern of the longitudinal stress (σ_{11}) on top surface of the HH10 tie loaded by an axle load of 200 kN with a frequency of 3 Hz. Increment: 65, total accumulated time: 1.35 sec. Maximum value of the longitudinal stress: 273 MPa for tension; 343 MPa for compression.

4.4. Displacement of the Tie Due to Dynamic Loads

In case when the HH10 tie is loaded by an axle load of 200 kN with a frequency of 7 Hz, the total accumulated time until increment 5 is 0.0446 seconds and until increment 75 it is 0.670 seconds. The total accumulated time until increment 5 is too short, it is not enough for the dynamic waves to propagate and to be generated due to the inertia of the tie. This statement is supported by comparing the *displaced shape* of the tie in *increment 5* (*Fig. 4.12*) and in *increment 75* (*Fig. 4.13*). In increment 5, only the rail-seat area of the tie is displaced, the middle section does not move. However, until increment 75, there is sufficient time for the dynamic waves to propagate. In *Fig. 4.13* the propagation of at least two wave peaks can be seen clearly in increment 75.

In real railway tracks, the tie receives the first load impulse gradually increased, due to the moving-approaching of the train. In other words, the first load impulse has a much lower frequency. In the laboratory the first load impulse is applied suddenly according to the frequency set in the machine. Based on this fact, *the first stress peaks in the calculations may be neglected and the stress peaks that occur in later increments should be taken into account.*

Therefore the values that should be considered as maximum values of the transverse normal stress are *516.7 MPa* in tension (node number 144201) and
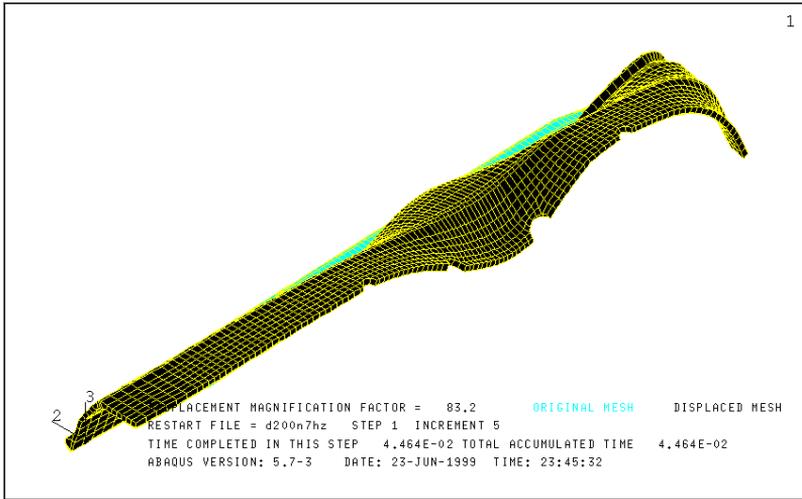
Fig. 4.12. Total displacement of the HH10 tie loaded by an axle load of 200 kN with a frequency of 7 Hz. Increment: 5, total accumulated time: 0.04464 sec. A quarter of the tie is indicated.
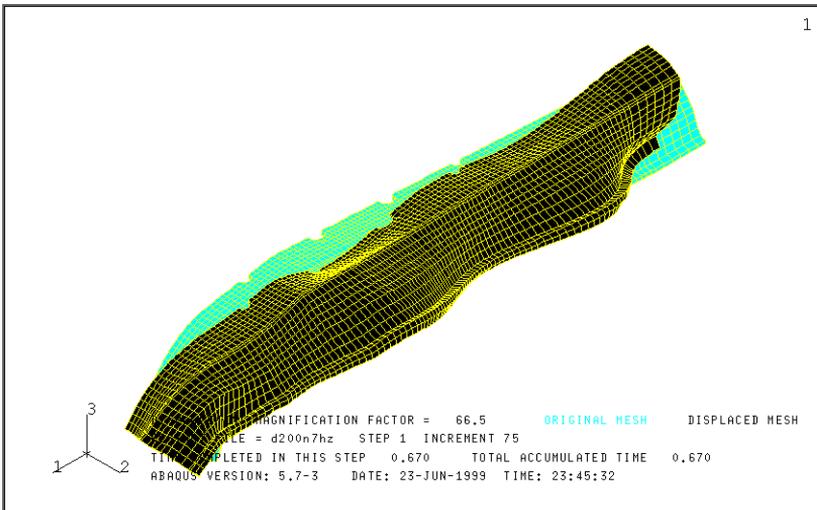
Fig. 4.13. Total displacement of the HH10 tie loaded by an axle load of 200 kN with a frequency of 7 Hz. Increment: 75, total accumulated time: 0.670 sec. A quarter of the tie is indicated.

467.5 MPa in compression (node number 144001).
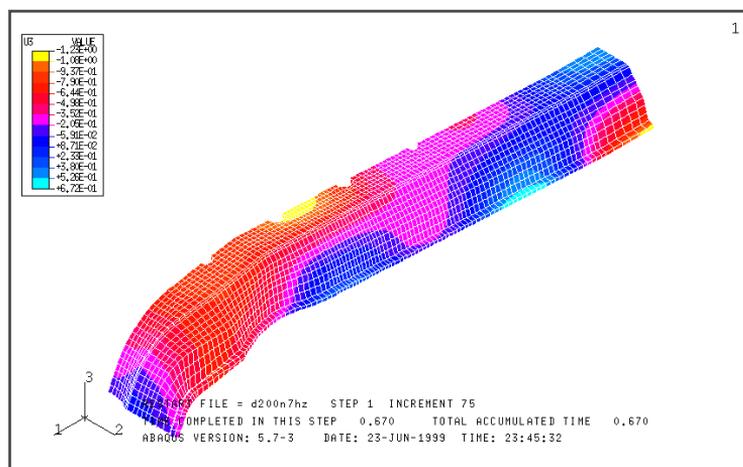
Fig. 4.14. Vertical displacement (u_3) of the HH10 tie loaded by an axle load of 200 kN
with a frequency of 7 Hz. Increment: 75, total accumulated time: 0.670 sec.
Maximum value of the vertical displacement: 1.23 mm downward; 0.672 mm
upward.

Fig. 4.14 shows the *vertical displacement* (u_3) of the HH10 tie loaded by an
axle load of 200 kN with a frequency of 7 Hz in increment 75. Its maximum value
is 1.23 mm downward and 0.672 mm upward. Greater vertical displacements will
occur in other increments. *Fig. 4.11* shows the original and the displaced shape of
the HH10 tie. The original, unloaded shape of the tie is illustrated in green colour
and the deformed shape of the loaded tie in dark brown colour.

Table 4.10 shows the values of the vertical displacement (u_3) of *node 144001*
in the same time-increments as those in *Table 4.1* ($f = 3$ Hz).

Table 4.10. Values of the vertical displacement of node 144001, in certain time increments
($f = 3$ Hz)

The number of increment	Total accumulated time [seconds]	Vertical displacement of node 144001 [mm]
6	0.125	2.634
35	0.729	1.664
65	1.35	1.461
94	1.96	1.616

5. Conclusions of the Dynamic Assessments of the HH10 Ties

Based on the results of the dynamic assessments of the HH10 ties, obtained in case of an axle load of 200 kN and 250 kN with frequencies of 3 Hz, 5 Hz, 7 Hz and 10 Hz, the following conclusions can be drawn:

- If the load is increased by a factor, all stress, strain and displacement responses will be increased by the same factor in the tie. Increasing the magnitude of the load will not modify the frequency of the response.
- The pattern of the *transverse stress* is the same in increments when it reaches its absolute maximum value or a local maximum value in function of time that is close to the absolute maximum. In such increments the pattern is independent of the frequency of the load (*Figs. 4.7–4.10*).
- When the transverse stress reaches its absolute maximum value or a local maximum value in function of time that is close to the absolute maximum, it will reach it in node 144001 for compression and in node 144201 for tension (*Figs. 4.7–4.10*).
- In increments when the maximum value of the transverse stress in the tie is much less than the absolute maximum value over the total assessment time period, the maximum value of the transverse stress will occur along the longitudinal plane of symmetry. This is either in a point of the end-spade-rounding or on the edge of one of ballast inspection wholes or of the fastening wholes.
- Irrespective of the frequency of the load, the absolute maximum value of the *longitudinal normal stress* σ_{11} is less than the half of that of the transverse stress in the same increment (*Fig. 4.11*).
- Where the transverse stress reaches its maximum value, the longitudinal stress has a neutral value and where the longitudinal stress reaches its maximum value, the transverse stress has a low value. The maximum values of the transverse and the longitudinal stresses do not occur at the same position, in the same increment (*Figs. 4.7–4.11* and *Tables 4.2–4.3*).
- Irrespective of the frequency of the load, the absolute maximum value of the longitudinal normal-stress or, a local maximum that is close to the absolute one may occur at either of two pairs of locations. One pair of location is on the edge of the outer fastening whole at the end of the radii perpendicular to the longitudinal plane of symmetry or on the outer-most edge of the side of the tie (*Figs. 4.11*).
- The *vertical normal-stress and the shear stresses* are in a neutral state on the top section of the tie in the regions where the transverse and the longitudinal stresses reach their maximum values.
- The frequencies of the stress *responses* in element 142001 of the HH10 ties to 200 kN of axle load with different frequencies differ from each other. It might be due to that the natural frequency of the system modelled in computation might be close to the frequency of the applied load (*Figs. 4.2, 4.4, 4.6*).

- The frequency of the stress, strain and displacement responses of the ties does not equal the frequency of the load (*Figs. 4.1–4.6*).
- There is no correlation between the frequency of the load and the maximum values of the stresses. With increasing the frequency of the load, the maximum values of the stresses neither strictly increase nor strictly decrease (*Tables 4.1*).

References

[1] Based on the Tie Fatigue Tests Carried out at the University of Illinois at Urbana-Champaign, USA, 1998–1999.
[2] Based on the Drawing of the tie Manufacturer. (Some sizes are intentionally missing), University of Illinois at Urbana-Champaign, USA, 1999.
[3] Getting started with ABAQUS/Standard Hibbitt, Karlsson & Sorensen, Inc. 1996.
[4] Personal communications.