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Verification of a Simulation Model for Resin Film Infusion of Complex Shaped Composite Structures

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ABSTRACT: Resin film infusion (RFI) has been found to be a cost-effective technique for the fabrication of complex shaped composite parts for primary structural applications. Dry textile preforms are infiltrated, consolidated, and cured in a single step, eliminating the labor to lay-up prepreg tape. The large number of processing variables and the complex material behavior during infiltration and cure make experimental optimization of the RFI process extremely inefficient.

The objective of this work was to develop and verify a three-dimensional model to simulate the RFI process. For a specified pressure and temperature cure cycle the code can predict resin pressure, viscosity and degree of cure, flow front progression, and temperature distribution in the preform and tooling components. The model was divided into submodels which describe resin flow, heat transfer, and resin kinetics. A finite element/control volume approach was used to model the flow of the resin through the preform. Boundary conditions include specified pressure, specified flow rate, and vents. A finite element formulation of the transient heat conduction equation was used to model the heat transfer. Thermal boundary conditions include either specified temperature or convection. The code was designed to be modular so the flow problem could be solved alone, or coupled with the thermal problem. The problems are solved sequentially in a quasi-steady state fashion.

Non-isothermal experiments with a reactive resin were conducted to verify the thermal module and the resin model. A two blade stiffened panel, fitted with sensors, was manufactured using the RFI process. Thermocouples were used to measure the temperatures, and FDEM (dielectric) sensors and pressure transducers were used to monitor the flow front progression. Model predictions and experimental results were found to be in close agreement for the temperatures and flow front progression. The predicted and measured infiltration times matched to within 12%, and the temperatures to within 5%.

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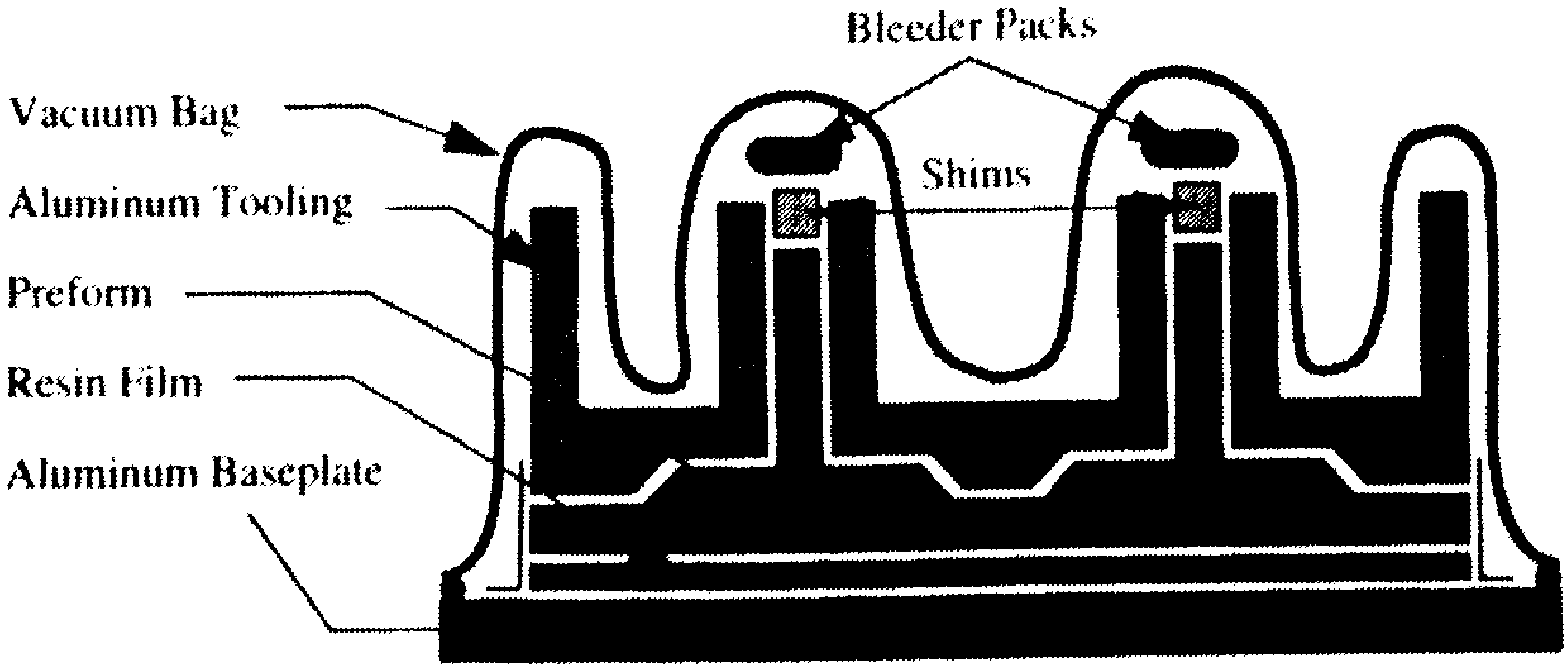


Figure 1. *RFI setup.*

INTRODUCTION

THE RESIN FILM infusion (RFI) process has been identified as a cost effective method for producing composite parts. High dimensional accuracy of the finished part can be attained because matched metal tooling is used. Also, complex shaped components can be readily fabricated. This allows for incorporation of many components into a single part and helps to reduce the cost and weight of the structure [1].

A diagram of the RFI setup for a two-blade, stiffened panel is shown in Figure 1. The RFI process begins with a dry fiber preform. A sheet of neat resin is cast and placed directly under the preform. Tooling blocks are then placed around the preform, and the assembly is vacuum bagged and placed in an autoclave. When the autoclave is heated and pressurized, the resin gradually melts and flows into the preform, and cures as the process progresses.

Due to the complex nature of the RFI process, experimental optimization of the process is not cost effective. A numerical approach was chosen to model the problem. The objective of this work was to develop and verify a comprehensive three-dimensional RTM/RFI simulation model. The model includes flow through a porous anisotropic preform, heat transfer through the preform and surrounding tooling, and cure kinetics of the resin. This model was used to confirm the validity of using measured one-dimensional permeabilities as principal permeabilities in a three-dimensional model.

RFI PROCESS SIMULATION MODEL

In this section a three-dimensional model is presented that can be used to predict the non-isothermal flow of resin through a fabric preform, and also predict the subsequent cure. The model is composed of three submodels. These include flow, heat transfer, and thermochemical submodels. For a given autoclave temperature and pressure cycle, the code can predict: a) flow progression, flow front location, and infiltration time; b) temperature distribution in the preform and tooling; c) cure and viscosity of the resin; d) resin pressure distribution in the preform.

Resin Flow Submodel

In any model of the RFI or RTM processes, one of the most important aspects is tracking the flow of the resin through the preform. The three-dimensional flow model was developed to calculate the pressure and velocity fields in the fluid and track the flow front position. This formulation is patterned after Davé [2]. The assumptions made in the formulation include: a) the preform is a heterogeneous, porous, anisotropic medium; b) the flow is quasi-steady state; c) capillary and inertial effects are neglected (low Reynolds number flow); d) the fluid is assumed to be Newtonian (its viscosity is independent of shear rate), and incompressible; e) the fluid does not leak from the mold cavity.

Assuming that the preform is a porous medium and that the flow is quasi-steady state, the momentum equation can be replaced by Darcy's law:

$$q_i = -\frac{S_{ij}}{\mu}\frac{\partial P}{\partial x_j} \tag{1}$$

where q_i is the superficial velocity vector, μ is the fluid viscosity, S_{ij} is the permeability tensor of the preform, and P is the resin pressure.

The continuity equation for the incompressible resin can be written as:

$$\frac{\partial q_i}{\partial x_i} = 0 \tag{2}$$

Substitution of Equation (1) into (2) gives the governing differential equation of the flow:

$$\frac{\partial}{\partial x_i}\left(\frac{S_{ij}}{\mu}\frac{\partial P}{\partial x_j}\right) = 0 \tag{3}$$

This second order partial differential equation can be solved when appropriate boundary conditions are prescribed. Two common boundary conditions for the inlet to the mold are either a prescribed pressure condition:

$$P_{inlet} = P_{inlet}(t) \tag{4}$$

or a prescribed flow rate condition:

$$Q_n(t) = n_i \frac{-S_{ij}}{\mu} \frac{\partial P}{\partial x_j} \tag{5}$$

where Q_n is the volumetric flow rate and n_i is the normal vector to the inlet. The boundary condition along the flow front is taken to be one of zero pressure:

$$P_{flow\,front} = 0 \tag{6}$$

Since the resin cannot flow through the mold wall, the velocity normal to the wall at the boundary of the mold must be zero:

$$q_i \cdot n_i = 0 \tag{7}$$

where n_i is the vector normal to the mold wall.

Heat Transfer Submodel

In the RFI process, the heating rates and flow rates are small compared to the RTM or SRIM processes. This allows a number of simplifying assumptions to be made in the thermal analysis. The bagged preform and tooling assembly are heated in the autoclave at a low heating rate, usually no greater than 5°C/min. As a result, the temperature difference between the resin and the preform is small during infiltration. Thus, the volumetric heat transfer between the resin and the preform can be neglected. Since the flow velocities of the resin are small, heat transfer due to convection between the resin and fiber can be ignored. This can be expressed mathematically with the Graetz and Peclet numbers listed by Tucker [3]. The Graetz number can be interpreted as the flow direction convection divided by the transverse conduction, and is given by:

$$Gz = \frac{qh^2}{\alpha_t L} \tag{8}$$

where q is the superficial resin speed, h is half of the mold thickness, L is the characteristic flow length, and α_t is the total thermal diffusivity defined as $(k_{zz}/(\rho c_p))$. k_{zz} represents the total effective conductivity in the thickness direction and ρ and c_p are the density and specific heat of the resin, respectively.

The Peclet number

$$Pe = \frac{qd_p}{\alpha_t} \tag{9}$$

Table 1. Values used to calculate the Graetz and Peclet numbers.

Variable	Value	Units
k_{zz}	0.822	W/(mK)
$2h$	0.01753	m
L	0.8255	m
d_p	8×10^{-6}	m
q	2.43×10^{-5}	m/s
ρc_p	1.267×10^{6}	J/(m^{3}°C)
Gz	0.0035	
Pe	0.0003	

where d_p is the diameter of a single fiber, can be interpreted as the ratio of dispersion to conduction.

Using numerical data from the two stiffener panel modeled in the next section, the Graetz and Peclet numbers were calculated. Table 1 lists the values used in the calculations. Since the Graetz and Peclet numbers are $\ll 1$, dispersion and convection can be neglected, and the entire model can be described by one temperature field.

The governing equation for the heat transfer in the RFI process model is based on the three-dimensional transient heat conduction equation, and includes a term for heat generation:

$$\rho c_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x_i}\left(k_{ij}\frac{\partial T}{\partial x_j}\right) - \rho\frac{dH}{dt} = 0 \tag{10}$$

where ρ is the mass density, c_p is the specific heat, k_{ij} is the thermal conductivity tensor for an anisotropic material, and dH/dt is the rate of heat generation due to exothermic chemical reactions.

In order to solve Equation (10), the initial temperature distribution must be given:

$$T(\bar{x},0) = T_{init}(\bar{x}) \tag{11}$$

where $\bar{x}$ is a position vector of a point. Boundary conditions for the solution of Equation (10) include insulated, specified temperatures, convection, and specified flux.

Thermochemical Submodel

In order to model the cure of the resin, a relationship must be found that gives the cure as a function of time. If the assumption is made that the rate of heat generation during cure is proportional to the rate of the cure reaction, then the degree of cure, α, of the resin can be defined as:

$$\alpha(t) = \frac{H(t)}{H_R} \tag{12}$$

where $H(t)$ is the heat evolved from the beginning of the reaction to some intermediate time, t, and H_R is the total heat of reaction during cure. To find an expression for the rate of heat generation, we differentiate and rearrange Equation (12) to give:

$$\frac{dH}{dt} = \frac{d\alpha}{dt} H_R \tag{13}$$

where $d\alpha/dt$ is defined as the reaction or cure rate. For a thermosetting resin, the cure rate depends on the temperature and degree of cure. The equation used to fit the cure rate as a function of cure is:

$$\frac{d\alpha}{dt} = c_1[k_1(1-\alpha)^{n_1}] + c_2[(k_2 + k_3\alpha^m)(1-\alpha)^{n_2}] \tag{14}$$

where n_1, n_2, and m are the temperature dependent kinetics constants, and k_1 and k_2 are the rate constants. The temperature dependence of the rate constants is given by an Arrhenius-type expression:

$$k_i = A_i \exp\left[\frac{-E_i}{RT}\right], \quad i = 1,2 \tag{15}$$

where A_i is the Arrhenius pre-exponential factor, E_i is the Arrhenius activation energy, R is the gas constant, and T is the absolute temperature. Values for these constants were found using a procedure similar to the one in Chen and Macosko [4], and are listed in Table 2.

If diffusion of chemical species and convection of the fluid are neglected, then the degree of cure at each point inside the material can be determined by integrating the cure rate with respect to time. To accurately predict the resin infiltration into the preform, the viscosity of the resin must be known as a function of both position and time. Resin viscosity is a complex function of shear rate, temperature, and degree of cure, and no analytical models exist to adequately describe this relation. However, a reasonable approach is to assume that the resin is a Newtonian fluid, and to measure the viscosity at low shear rates. The measured viscosities can

Table 2. 3501-6 reduced catalyst high temperature cure kinetics model constants.

	Value	Units
A_1	2.516×10^8	sec^{-1}
A_2	40.35097	sec^{-1}
A_3	8.7355×10^7	sec^{-1}
E_1/R	10.90214	Kelvin
E_2/R	5.28071	Kelvin
E_3/R	11.2061	Kelvin
n_1	0.8817	T in Kelvin
n_2	$(0.029598T) - 3.28439$	
m	0.96398	
C_1	0.05	
C_2	0.95	
H_R	430.0	kJ/kg
ρ	1260	kg/m^3

then be fit by a mathematical expression relating temperature and time to viscosity, and the resulting formula can be used in the numerical calculations. Here a formula based on the work of Castro and Macosko [5] is used:

$$\mu(T,\alpha) = \mu_0(T)\left[\frac{1}{1-\alpha}\right]^{A(T)+B(T)\alpha} \tag{16}$$

where μ is the viscosity, μ_0 is the viscosity at zero cure, T is the temperature, and A and B are parameters which depend on temperature.

The viscosity-time characteristics of the reduced catalyst resin were measured at elevated temperatures using a Bohlin rheometer. Viscosity measurements were made using 25 mm diameter parallel plates. An appropriate quantity of resin was used in order to maintain a plate gap of 1–2 mm. The cure reaction kinetics model was used to convert the isothermal viscosity-time curves to viscosity-cure curves. For temperatures above 90°C the resin viscosity was fit with the following equation:

$$\mu_0 = 7.875 \times 10^{10} \exp\left[\frac{7765}{T + 273}\right]$$

$$A = 4.151$$

$$B = -17.831 + 0.147T$$

where μ is the viscosity in Pa·s, α is the degree of cure, and T is the temperature in °C.

Since the heating rates used to heat the composite/tool assembly in the RFI process are slow, resin flow and complete wet out often occur before the autoclave reaches 90°C. As a result there is a need for a low temperature viscosity model. A Brookfield viscometer was used to perform isothermal viscosity measurements between 60 and 90°C. The cure of the resin was also measured by DSC at temperatures below 90°C, and it was found that the advancement of the resin was no more than 5–8% for times up to 8 hours. To obtain a fit to the data, it was assumed that there is no significant cure below 90°C, and the viscosity in the low temperature region depends only on the temperature. The data were fit with an Arrhenius model:

$$\mu(T) = 4.0074 \times 10^{16} \exp\left[\frac{12994.9}{T + 273}\right] \tag{17}$$

where μ is the viscosity in Pa·s.

NUMERICAL APPROACH

A computer program called 3DINFIL was written to simulate the RTM/RFI process. The program takes as input two finite element models. The first model contains the finite element mesh of the preform and any other flow regions, and includes the flow boundary conditions. The second model contains the finite element mesh of the preform, tooling, and any other geometry that is needed for the thermal analysis. It also includes the thermal boundary conditions. The program also requires the input of the processing cycle, including temperature and pressure cycles.

The finite element models are constructed using 8-noded hexahedral elements. Both the flow and heat transfer models must use the same mesh in the preform region to allow for exchange of data between the two models.

The program is composed of three sub-models: the flow model, the heat transfer model, and the thermochemical model. All three models are coupled and nonlinear. The flow model needs the viscosity from the resin model, the resin model needs the temperatures from the heat transfer model, and the heat transfer model uses the heat generation from the resin model. Instead of trying to solve the coupled system, the problem is solved in a segmented approach where each submodel is treated separately. In addition, each submodel is solved in a piecewise linear fashion. This not only reduces the coding and solution effort, it also allows the code to be in a 'modular' form, with each submodel in its own module. This way each module can be turned on and off individually depending on the particular analysis being performed.

Since the program was written in standard Fortran 77, it has proven to be easily portable to different computers and operating systems. Currently, the code has been successfully run on Silicon Graphics, HP, and Cray computers.

The program uses a three-dimensional finite element/control volume (FE/CV) method [6] to track the flow of the resin through the preform. A time dependent finite element scheme is used to calculate the temperatures. The finite element models were created in the solid modeling package PATRAN. Meshes were created and boundary conditions including specified pressures, vent locations, and heat transfer coefficients were applied. Visualization of the results was also completed using PATRAN.

To reduce the amount of memory needed, the stiffness matrix is stored in a sparse storage format. The code currently uses the NASA General Purpose Solver (GPS) to solve the equations [7].

EXPERIMENTAL WORK

A panel with two stiffeners was manufactured using the RFI process. A two stiffener panel was chosen because the complex shape introduces a three-dimensional flow pattern. The preform skin was constructed of eight stacks of warp knit fabric and the blades were constructed from 14 tube braided material. A sketch of the preform is shown in Figure 2.

The mold for the two stiffener panel was constructed from 6061-T6 aluminum. A sketch of the tooling is shown in Figure 1. The base plate was approximately 121.92 cm long by 60.96 cm wide by 1.27 cm thick. The thickness of the upper mold components varied from about 1.4 to 2.3 cm.

Mounted in the molds were four Entran flush mount pressure transducers, model EPX0-X03-150P and three FDEM (dielectric) sensors. Eight thermocouples were mounted in and around the panel. The locations of the sensors are

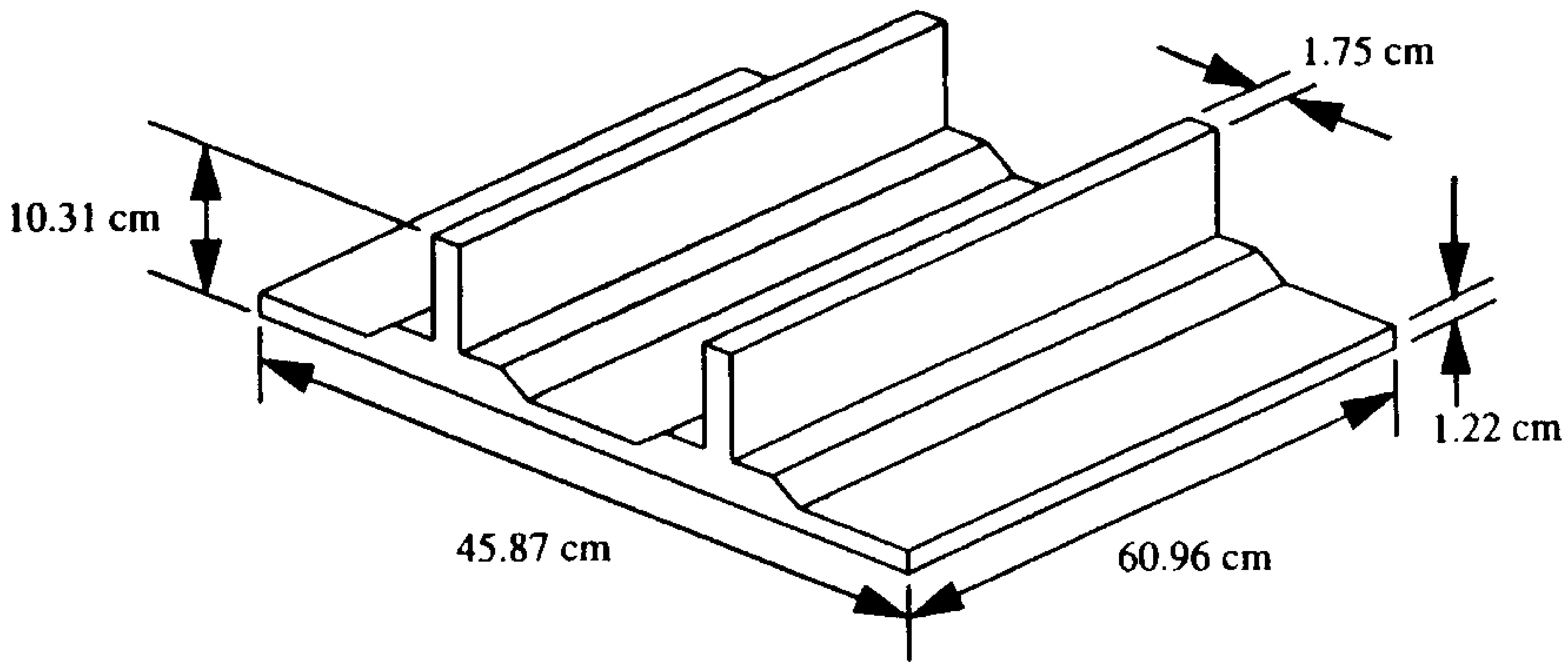
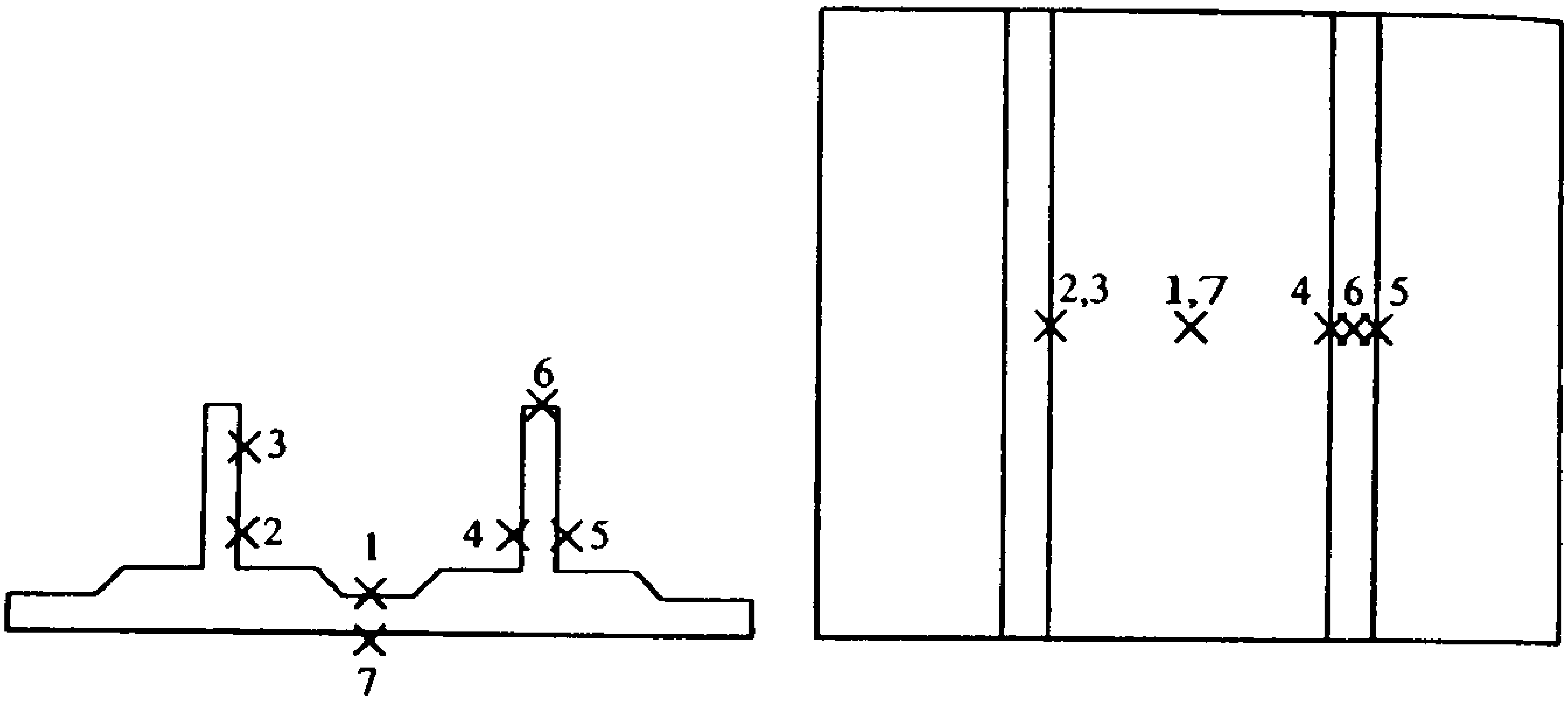


Figure 2. *Sketch of the two stiffener preform.*



Front View

Top view

Figure 3. Locations of the sensors on the two stiffener panel.

shown in Figure 3. Table 3 shows the type of sensor at each location. The thermocouple at location 1 was mounted between the resin film and the base plate, and the thermocouple at location 7 was mounted between the skin and the center tool. The remaining six thermocouples were mounted in the autoclave air about 5 cm away from the assembly.

RESULTS AND DISCUSSION

The process was simulated using 3DINFIL and the numerical results were compared to the experimental results. The objective of the test was to verify the flow, heat transfer, and thermochemical models in a complex shaped RFI part. The finite element mesh used in the simulation is shown in Figure 4. The flow model was

Table 3. Correspondence between the locations and sensors.

Model Location	TC	Pressure Transducer	FDEM
1	X	X	X
2			X
3		X	
4		X	
5		X	
6			X
7	X		

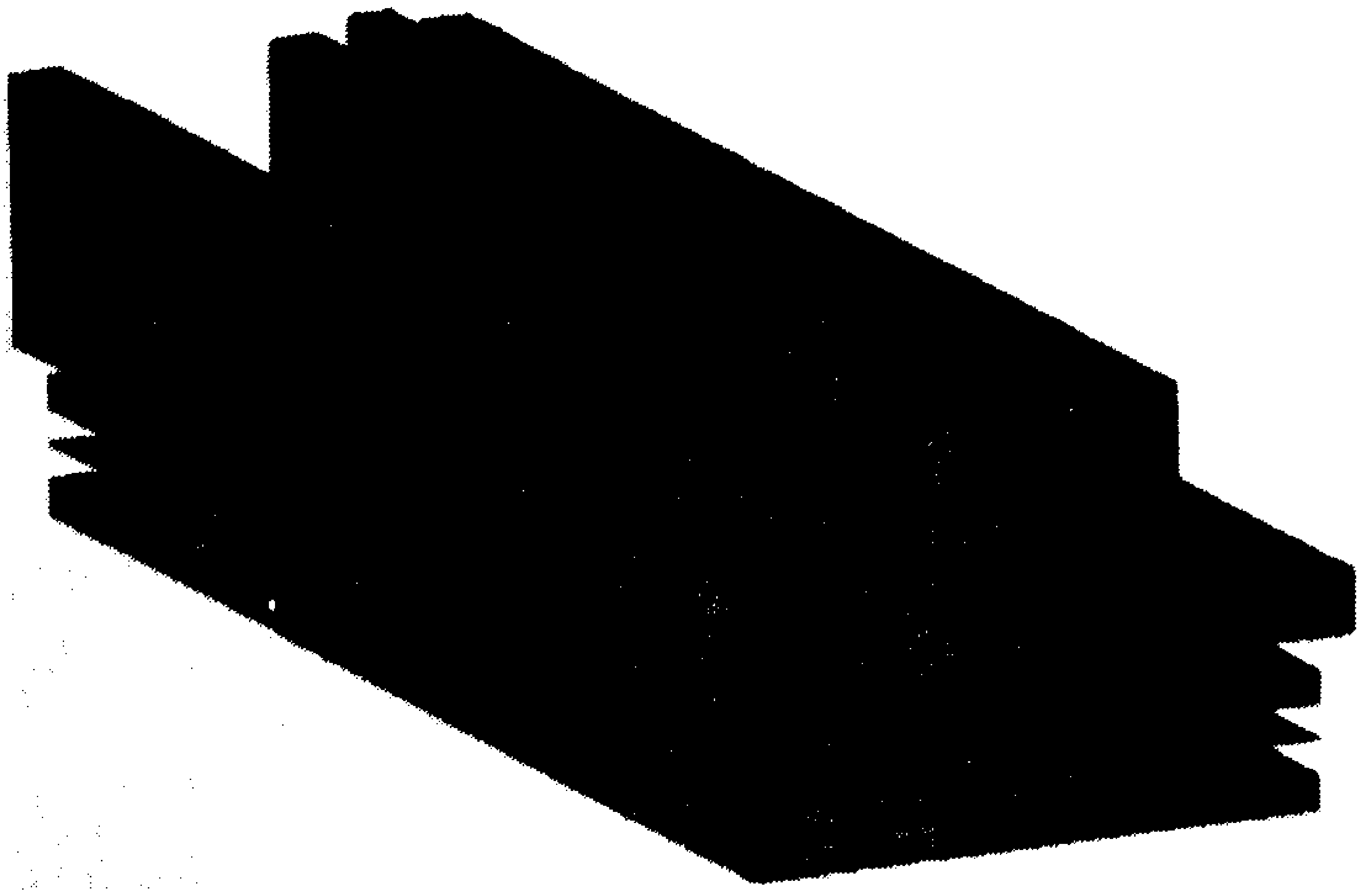


Figure 4. Mesh used in the finite element model of the two stiffener panel.

composed of 8995 nodes and 7276 elements, and the thermal model contained 17,325 nodes and 14,994 elements. The model took approximately 78 CPU hours on an SGI Origin 200 with an R10000 processor.

Half symmetry was exploited to reduce the size of the model. The sensors in the actual part were distributed between the two stiffeners, but the model only had one stiffener. It was assumed that the process would be symmetric between the two stiffeners.

Boundary Conditions

In the flow model the autoclave pressure was applied to the lower surface of the skin. The pressure started at 1 Pa and ramped to 827 kPa in 10 minutes, then was held constant for the duration of the process.

The measured autoclave temperatures are shown in Figure 5. The thermal model used the measured autoclave temperatures as boundary conditions. It should be noted that thermocouple 3 recorded a much lower air temperature than the other thermocouples. One of the heating coils in the autoclave did not work, and thermocouple 3 was nearest to the cooler area.

Temperatures

Measured and predicted temperature profiles are shown in Figure 6. Predicted and measured temperatures matched to within ±6%. The model initially overpredicts, then underpredicts the temperatures at location 1. This is most likely due to the presence of the breather material placed over the surface of the part when it

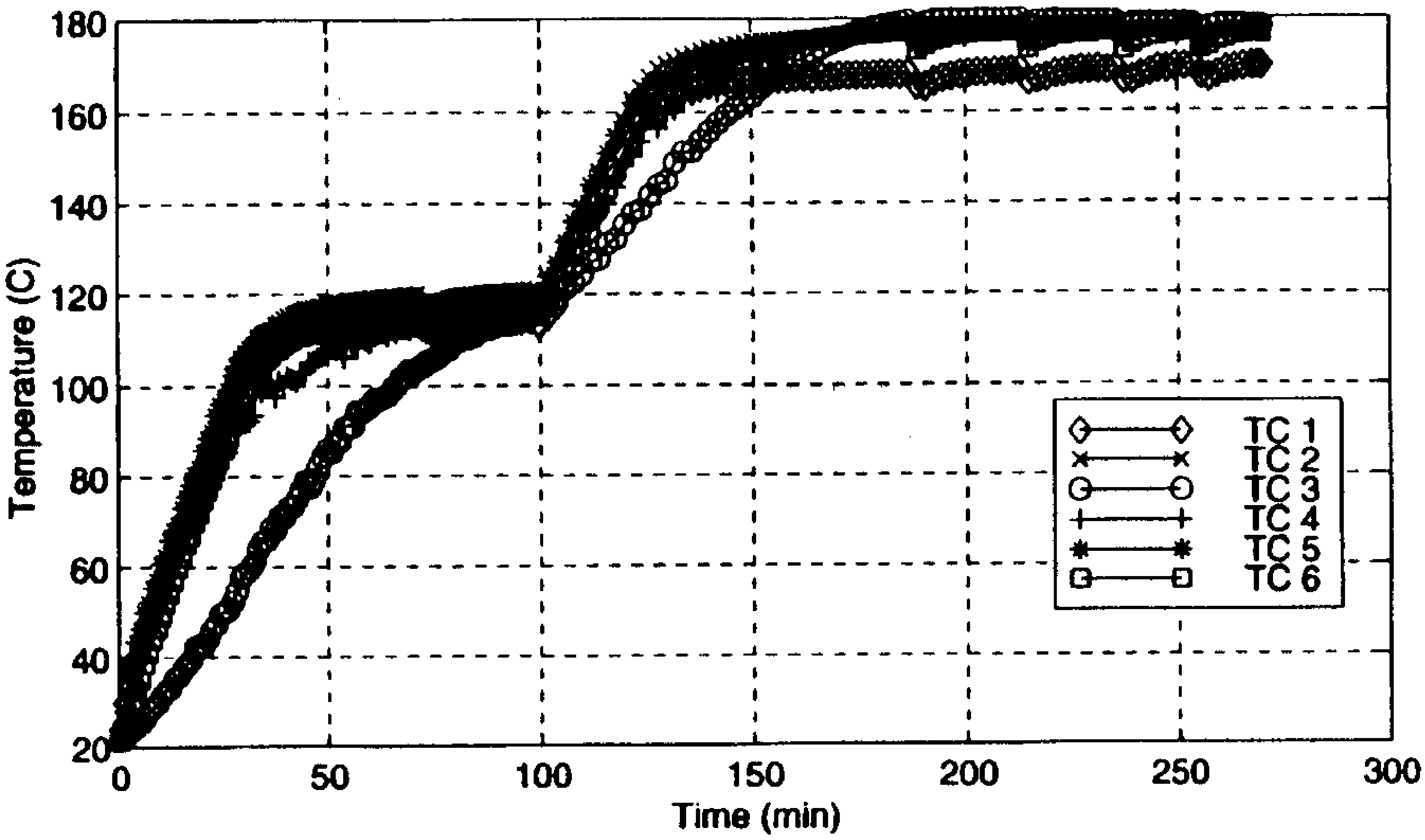


Figure 5. Measured autoclave air temperatures used in the two stiffener model. Thermocouple locations are shown in Figure 3.

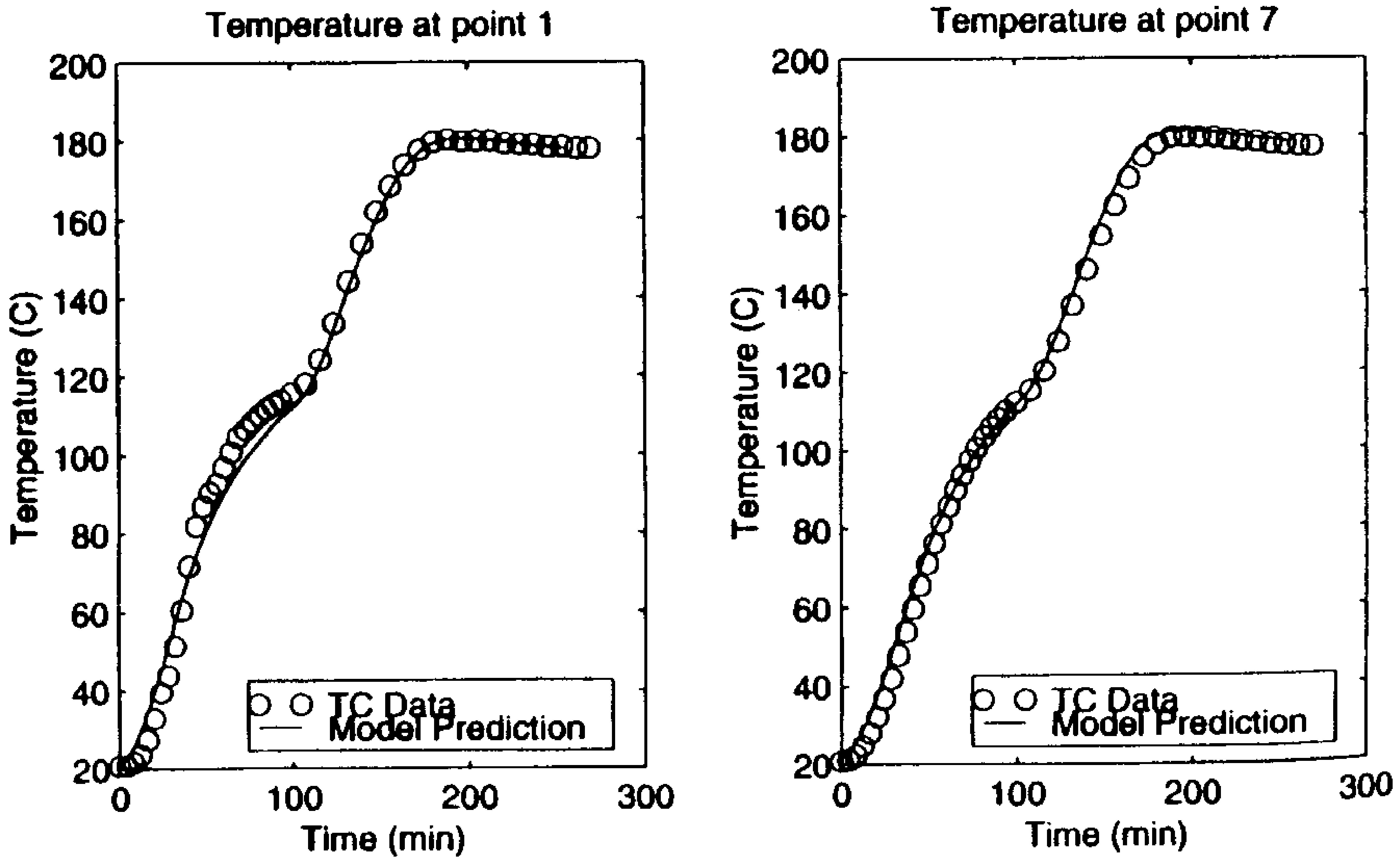


Figure 6. Measured and predicted temperatures in the two stiffener panel.

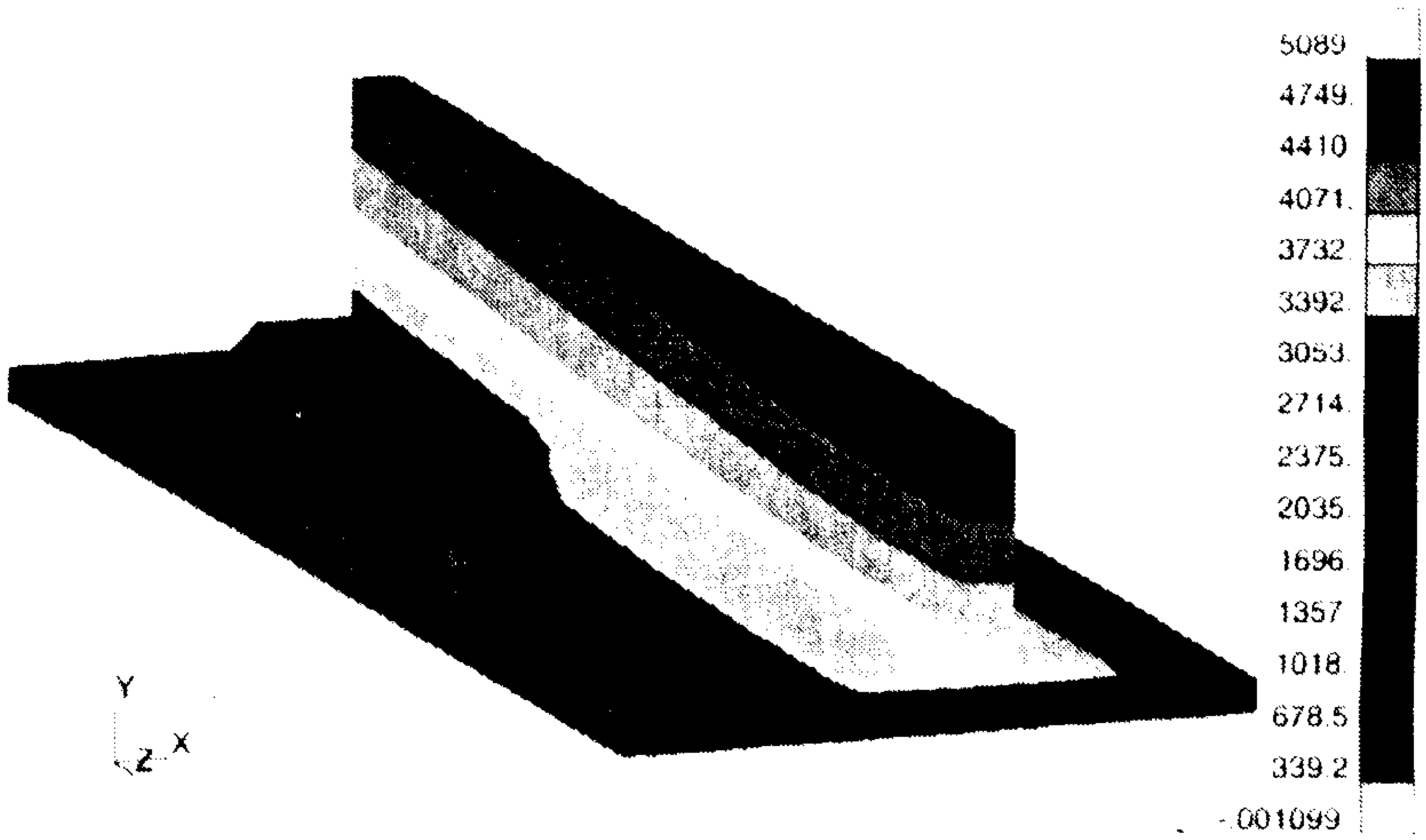


Figure 7. *Predicted flow front progression. the color bands represent the flow front location at different times. The units are in seconds.*

was autoclaved. The breather material is a glass fiber cloth that has low thermal conductivity. Since the breather was not included in the model, it may be a source of error.

Fill Times

The predicted flow front progression is shown in Figure 7. Figure 8 shows the wet out times for the various sensor locations. The model predictions were gener-

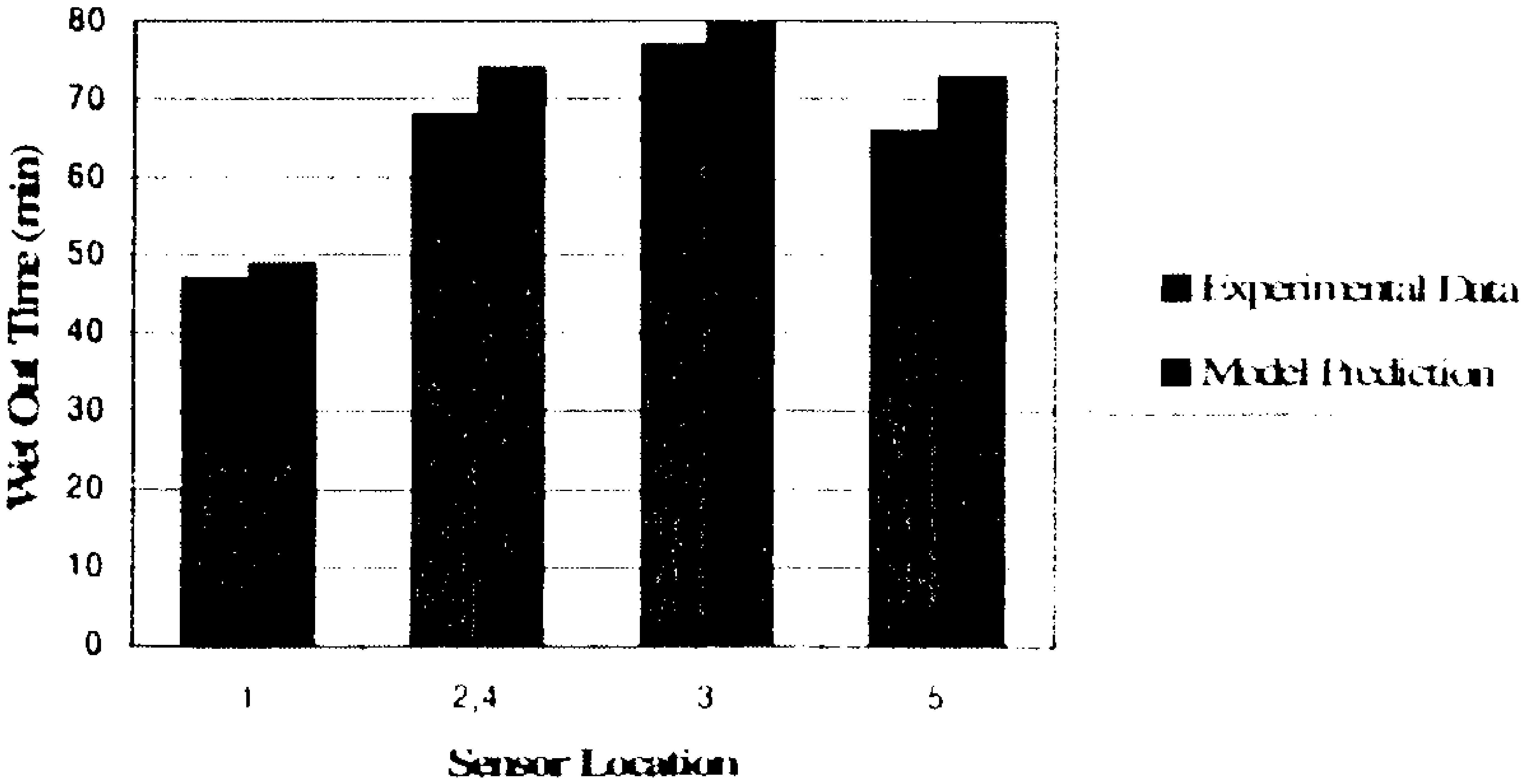


Figure 8. *Predicted and measured infiltration times for the two stiffener panel.*

ally conservative. All of the predicted wet out times were longer than the experimentally measured times. The closest match in wet out times was at location 4 where the prediction was within 4% of the average of the measured times. The difference in the measured and computed wet out times of the other locations varied from 7% to 12%.

CONCLUSIONS

A three-dimensional finite element code capable of simulating the RFI process has been developed. A two-blade-stiffened panel, fitted with sensors, was manufactured using the RFI process. Computed values of the wet out times and temperatures at several locations in the manufactured part are found to match well with the observed values.

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