Long-term Behaviour of CFRP-laminate-strengthened Concrete Beams at Elevated Temperatures

T. ULAGA and U. MEIER
EMPA Duebendorf, Switzerland

ABSTRACT

To investigate the long-term behaviour of CFRP-laminate-strengthened concrete at elevated temperatures and high humidities, two post-strengthened, steel-reinforced concrete beams with a span of 2.3 m were exposed to sustained flexural loads in a climate chamber. The temperature and humidity were increased over a period of several months. A comprehensive measurement system was employed to record strain and displacement. The test data allowed conclusions to be drawn about the deformational behaviour and limiting climatic conditions for CFRP strengthening systems. One laminate was based on an epoxy, the other on a thermoplastic matrix system.

INTRODUCTION

Today, carbon-fibre-reinforced plastic (CFRP) laminates are widely used for strengthening concrete structures. Of the many facility types to which these systems are applied, probably the most common are bridges [1] and residential, office and industrial buildings, where climatic conditions tend to remain moderate. Laboratory investigations have proved the efficiency and durability of CFRP laminates for such applications [2,3], and these results have formed the basis for dimensioning and detailing the strengthening works [4,5].

Climatic conditions in tropical regions or in buildings housing industrial plant may impose exceptional demands (e.g. temperatures permanently above 40°C coupled with high humidity) that cast doubt on the suitability of CFRP laminate in such situations. At the same time, CFRP strengthening systems may represent the most or even the only appropriate rehabilitation method in such cases.

The individual components of a strengthened structure (concrete body, steel bars, CFRP laminate, adhesive) react differently to fluctuations in temperature and humidity. Although these characteristics are known, it is difficult to predict the behaviour of combined systems and define the limiting conditions.

To investigate these issues, a long-term experiment was carried out in a climate chamber.

BACKGROUND

Test specimens

The aim was to test standard concrete beams reinforced with steel bars and strengthened with CFRP laminates.

Real structures tend to require strengthening only after reaching a certain age, and old concrete is much less susceptible to creep than young concrete. To make allowance for this, 15-year-old beams provided by the Institute of Structural Engineering (IBK) at the Swiss

Federal Institute of Technology (ETH) in Zurich were used for the tests. The geometry is shown in Figure 3.

Characterization of materials

Concrete

The concrete body serves to form the flexural compression zone and transfer internal shear stresses.

Overall, the concrete deformation consists of four strain components [6]. The stresses caused by loading the concrete element produce an initial strain. Loads and stresses sustained over a longer period result in creep – this strain component may be particularly significant if the concrete is loaded at an early age. Shrinkage strains develop during hardening. Thermal strains occur where the concrete body (regardless of its age) is heated or cooled and may be determined using the coefficient of thermal expansion $\alpha_T = 10^{-5}\ K^{-1}$.

<u>Concrete mix</u>

Max. aggregate size	Ø	16 mm
Cement content		325 kg/m^3
Water-cement ratio		0.45

Steel

Deformation of steel reinforcing bars in standard concrete structures is generally caused by stress, with thermal strain generally playing a minor role.

<u>Reinforcing bar properties</u>

Diameter	$Ø_s$	14 mm
Young's modulus	E_s	210 GPa
Yield stress	f_y	520 MPa

CFRP laminates

CFRP laminates may be bonded to the relevant beam surface as additional tension chord reinforcement where the expected flexural tensile stresses exceed the capacity of the steel bars.

The greater part of the strain is caused by flexural tension. Though thermal strain may also occur, this is very modest compared to thermal movement in steel or concrete [7]. The laminate matrix may absorb water when exposed to high humidity, and this, in turn, may affect the material strength and strain.

Two different laminates were investigated in the tests: beam *CaDu* was strengthened with the commercial product "Sika CarboDur S512", while a recently developed laminate was tested on beam *THELA*. The latter comprises carbon fibre embedded in a thermoplastic matrix system (unlike traditional laminates such as Sika CarboDur S512, which generally use an epoxy-resin matrix).

<u>Laminate properties</u>

		Sika Carbo-Dur S512	Thermoplastic laminate
Width	b_l	50 mm	50 mm
Thickness	t_l	1.2 mm	1.15 mm
Young's modulus	E_l	approx. 161 GPa	approx. 130 GPa
Strength	f_{lu}	min. 2800 MPa	min. 2300 MPa

Adhesive

The adhesive transmits shear stresses from the concrete to the CFRP laminate, i.e. the adhesive must exhibit a high shear modulus and creep resistance. The commonly used epoxy adhesives are therefore mixed with an inorganic filler. Thermal performance is a key factor: the mechanical properties change radically once the glass transition temperature of the epoxy resin has been exceeded.

The epoxy adhesive "Sikadur 30" was used to bond the laminate. A torsion pendulum test [8] was carried out to investigate temperature performance [3]. Figure 1 shows the changes in shear modulus: this remains high up to a temperature of approx. 42°C, before the material softens and deformation increases. The glass transition temperature T_g is defined as the temperature corresponding to the mid-point in the steep section of the shear modulus curve (55°C); however, this is of limited relevance here as the adhesive starts to soften at 42°C. As stiffness and strength diminish, the adhesive is no longer able to transmit the shear stresses. Structural failure may then occur due to peeling off of the laminate.

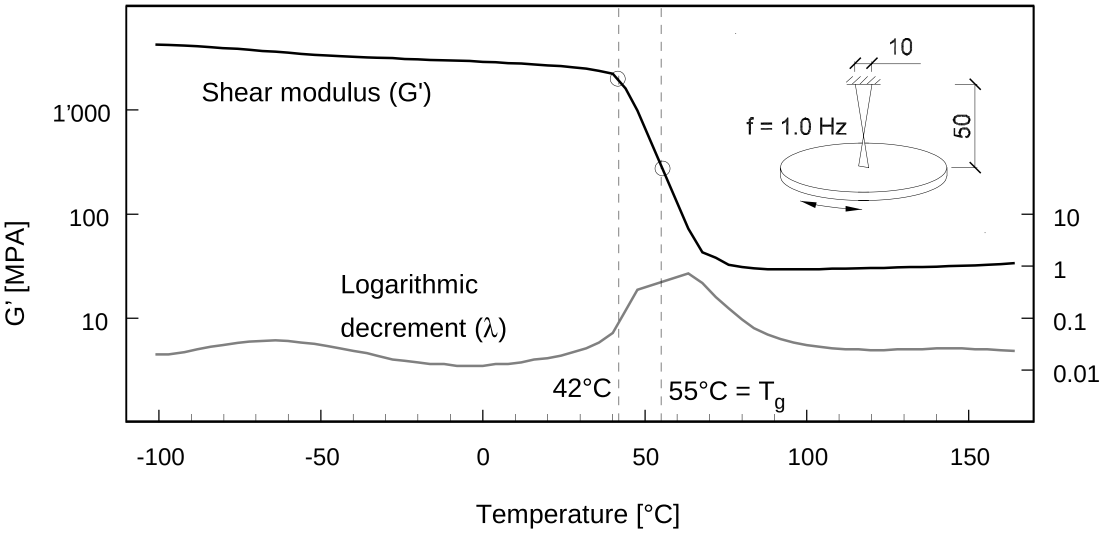

Figure 1: Torsion pendulum test: temperature dependence of shear modulus

Overall performance of cross-section

The deformation mechanisms of the individual cross-section components have been briefly outlined above. Comprehensive literature is available showing how these strains are estimated (e.g. [6]).

When the components are combined to form a single cross-section, interactions occur that considerably complicate prediction of deformation.

LABORATORY TESTS

Test set-up

The experiments were carried out in a climate chamber. The limited space and high test loads required construction of an appropriate testing facility (Figure 2).

The specimens were supported in the middle and loaded with concrete cubes at the ends in order to realize four-point bending (Figure 3). This arrangement allowed a bending moment of 17.6 kNm to be achieved at midspan. This level corresponds to the maximum serviceability limit state with the steel remaining just below its yield strain (Figure 5).

Figure 2: Testing facility

Test programme

The experiment was designed to test heavily loaded CFRP-strengthened concrete beams under elevated long-term climatic conditions. The limiting components with regard to temperature are the synthetic materials. As described above, the adhesive starts to soften at approx. 42°C. When exposed to humidity, the polymers absorb water which may affect their mechanical properties. Hence, the thermoplastic matrix of the newly developed laminate in particular was viewed as potentially problematic.

The test was set up at room temperature. After loading, the temperature was raised to 40°C and relative humidity adjusted to 30%. These atmospheric conditions were maintained for several weeks until deformations stabilized. Conditions were subsequently adjusted and again maintained until growth in deformation almost ceased.

Measurement programme

The aim of the comprehensive measurement programme (Figure 3) was to collect detailed information on the process of deformation in the test specimens.

A series of Demec gauges with a segment length of 200 mm were applied to the top and side faces of the specimens. Monitoring of these gauges allowed the corresponding strains to be determined. The creep behaviour of the (adhesive) interface was investigated by measuring the relative displacement, Δ, between laminate and concrete surface at the end of the laminate. Global deformation was recorded by deflection measurements at the ends of the specimens.

A combined temperature/humidity measurement device installed in the middle of the chamber was used to monitor atmospheric conditions.

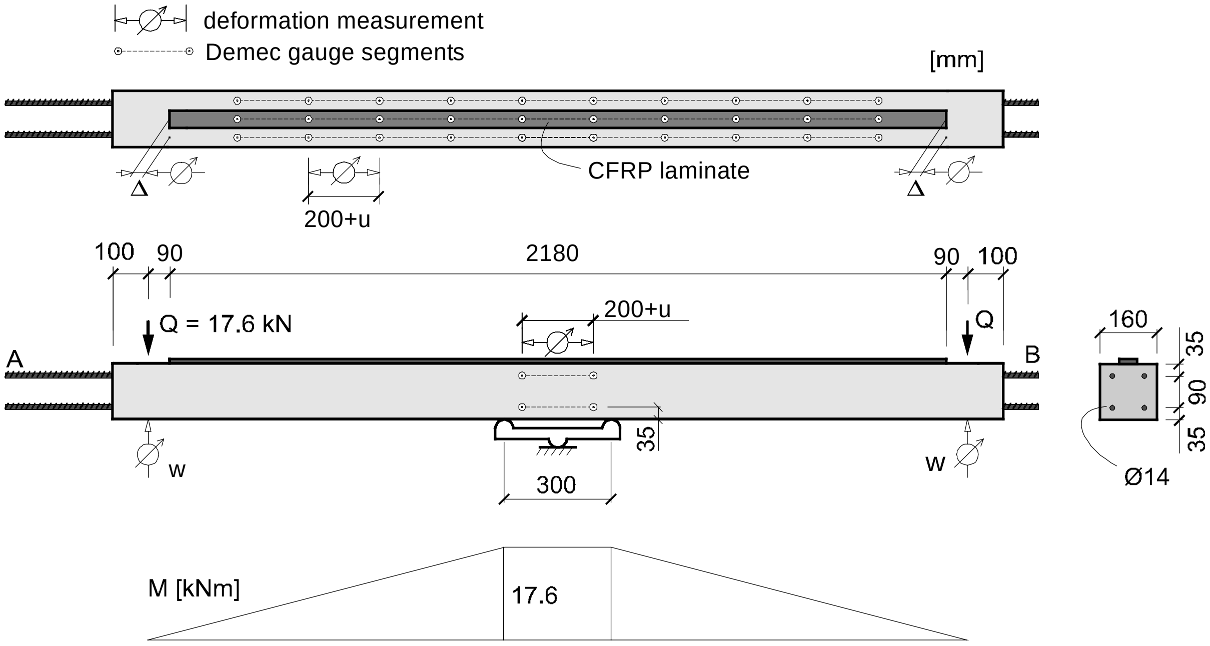

Figure 3: Load arrangement, geometry and measurement programme

RESULTS

Progress of the experiment

As mentioned above, regulation of the atmospheric conditions in the chamber was dictated by the deformation behaviour of the test specimens. The progress of the test between 2 February and 21 September 2000 is detailed below. The temperature and humidity measurements are shown in Figure 4.

Climatic conditions	Beginning – end	Duration
	29 February 2000	
Period 1: approx. 40°C, 30% r.h.		48 days
	17 April 2000	
Period 2: approx. 40°C, 80% r.h.		79 days
	5 July 2000	
Period 3: approx. 45°C, 80% r.h.		78 days
	21 September 2000	
		205 days (total time)

Deformation

The midspan deflection is shown in Figure 4. The dots relate to measurements made at intervals of between one and seven days. Figure 4 also shows the relative displacement, Δ, of the laminate ends.

Seven Demec gauge segments were monitored in the middle part of the beams: two on either side face, two on the top face and one on the laminate (Figure 5). Linear regression of the corresponding strains yielded the average deformation of the cross-section. The lines in Figure 5 show the state of the cross-section at the end of each climate period. The inclination of these lines is equal to the curvature of the beam.

Table 1 gives the deformations measured at the end of each climate period.

Table 1: Characteristic deformation at the end of each climate period

	THELA					CaDu				
Date	w [mm]	Δ_A [mm]	Δ_B [mm]	χ [m^{-1}]	ε_l [%]	w [mm]	Δ_A [mm]	Δ_B [mm]	χ [m^{-1}]	ε_l [%]
29.2.	12.30	-0.002	0.001	0.0305	0.34	11.10	0.000	-0.002	0.0247	0.30
17.4.	14.12	0.006	0.014	0.0334	0.37	12.23	0.010	0.009	0.0263	0.32
5.7.	14.61	0.016	0.028	0.0340	0.37	12.68	0.019	0.021	0.0268	0.32
21.9.	14.88	0.052	0.065	0.0360	0.39	13.19	0.051	0.057	0.0293	0.35

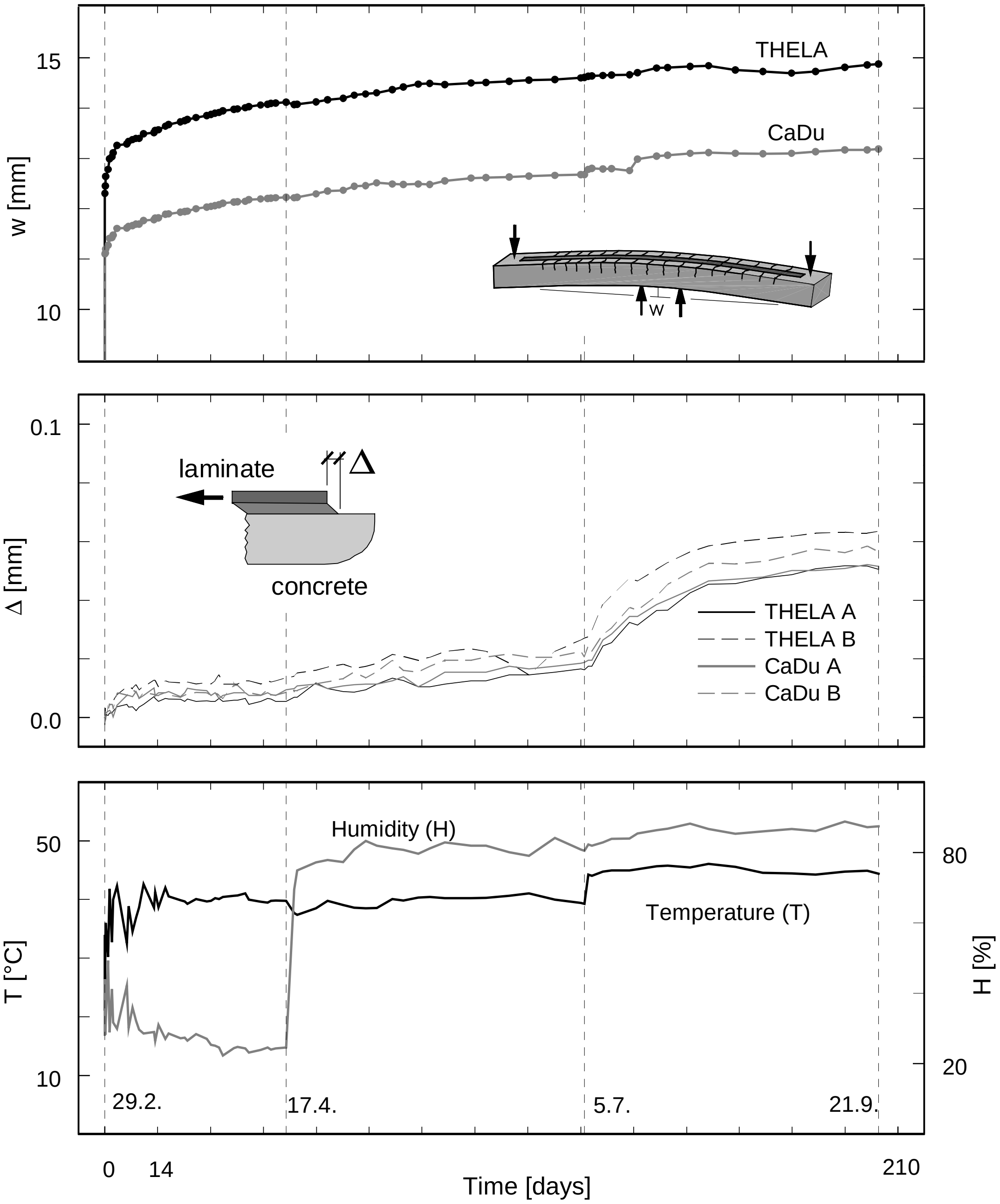

Figure 4: Deflection w, relative displacement Δ and changes in climatic conditions

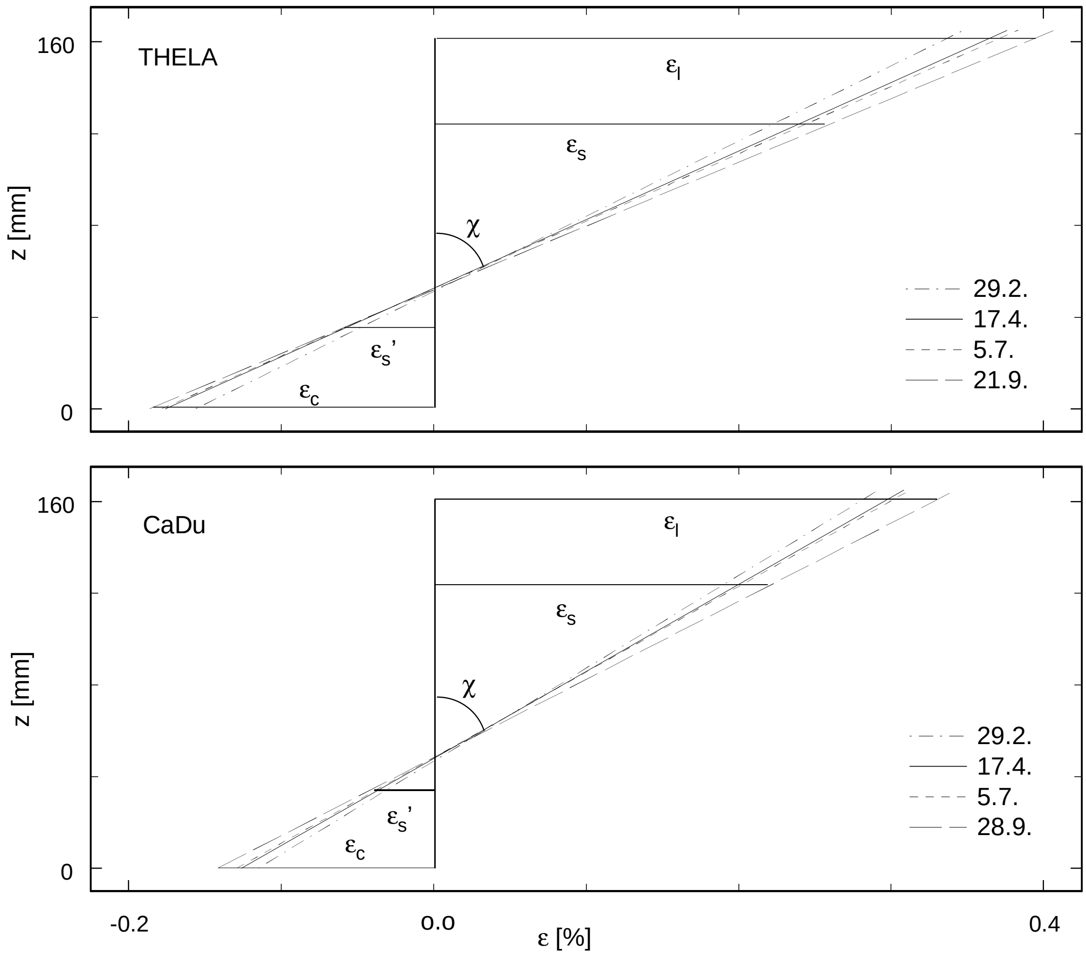

Figure 5: Average deformation of the cross-section at the end of each climate period

DISCUSSION

Loading of the specimens caused an initial midspan deflection of approx. $^{1}/_{200}$ of the span (the deflection of THELA is slightly greater due to the softer laminate; see Figure 4). An increase in these deformations was recorded at the beginning of the first climate period, but creep largely ceased after some weeks. The transition between the first and second climate periods appears very smooth, with only a slight discontinuity in the deflection line. In climate period 3, the temperature at which the epoxy adhesive starts to soften (Figure 1) was exceeded. The relative displacement, Δ, thus rose sharply at the beginning of this period. All deformations again levelled off after a few weeks.

The variations in curvature shown in Figure 5 may be used to assess the impact of the individual causes of deformation. During the first climate period, the specimens were exposed to constant stress and constant atmospheric conditions. The increase in curvature may thus be interpreted as creep deformation. The changes in concrete strain, ε_c, may be construed as creep deformation in the material, whereas the strain variations in the tension zone probably stem from creep at the steel–concrete and CFRP–concrete interfaces. The compression zone depth remained constant due to the equilibrium between these strain variations.

As Figure 4 shows, creep deformation ceased towards the end of climate period 1. In period 2, curvature remained more or less constant. The high humidity hardly affected deformation, and the slow creep process at the end of period 1 continued.

The temperature was raised by 5°C in climate period 3. The resulting thermal strains of steel and concrete were in the order of 0.005% and thus had only a minor impact on the overall deformation of the specimens. Thermal deformation of the CFRP laminate was even smaller. By contrast, the rise in temperature had a significant impact on the epoxy adhesive, which started to soften, and substantial creep deformations were recorded (Figure 4). As a result, the curvature increased further.

CONCLUSIONS

The values and limits derived from the experimental results are only valid for the tested CFRP strengthening systems. Further tests are required for other systems. Nevertheless, a number of general statements can be made:

Commonly used CFRP strengthening systems tend to be more sensitive to elevated temperatures and humidities than steel or concrete. To establish the limiting conditions for application, the limiting component of the cross-section must be investigated. In the described tests, initial softening of the epoxy adhesive was expected at a temperature of 42°C. This was confirmed by the experimental results: the CFRP-concrete bond started to soften when the temperature was increased from 40°C to 45°C. One positive finding is that the deformations stabilized under sustained loading after a couple of weeks and no structural failure occurred. This may be viewed as an additional safety reserve in case the softening temperature is exceeded.

The glass transition temperature, T_g, is frequently used in defining the limiting thermal conditions for synthetic components. However, this parameter is of limited relevance as the mechanical properties of the epoxy adhesive actually start to change at a lower temperature.

Overall, creep deformation appears to be very limited. This may be due to the use of old concrete beams with relatively high creep resistance.

The precise impact of humidity remains unclear. Although it can generally affect the strength of polymers, it is unlikely to affect the materials in the climatic and stress ranges of the present experiment.

The above results relate to the test period ending 21 September 2000. The experiment is not yet concluded and ongoing monitoring is planned.

ACKNOWLEDGEMENTS

The tests were performed as part of a joint-venture project with Sulzer Innotec AG (Winterthur, Switzerland) and Sika AG (Zurich, Switzerland). The financial support of the Swiss Commission for Technology and Innovation (KTI) is gratefully acknowledged.

The valuable assistance of H. Altorfer, J. Regnault, F. Stenger, I. Stoecklin, W. Trindler and A. Winistoerfer is highly appreciated.

NOTATION

A	at location A
B	at location B
E	Young’s modulus
G	shear modulus
H	Humidity
M	bending moment
T	Temperature
b	Width
f	Strength
u	Displacement
w	Deflection
z	beam depth coordinate
Δ	relative displacement
α	Coefficient

χ	curvature
ε	strain
λ	logarithmic decrement

Subscripts

T	thermal
l	laminate
s	steel
u	ultimate
y	yield

Superscripts

’	at compression

Symbol

Ø	diameter

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