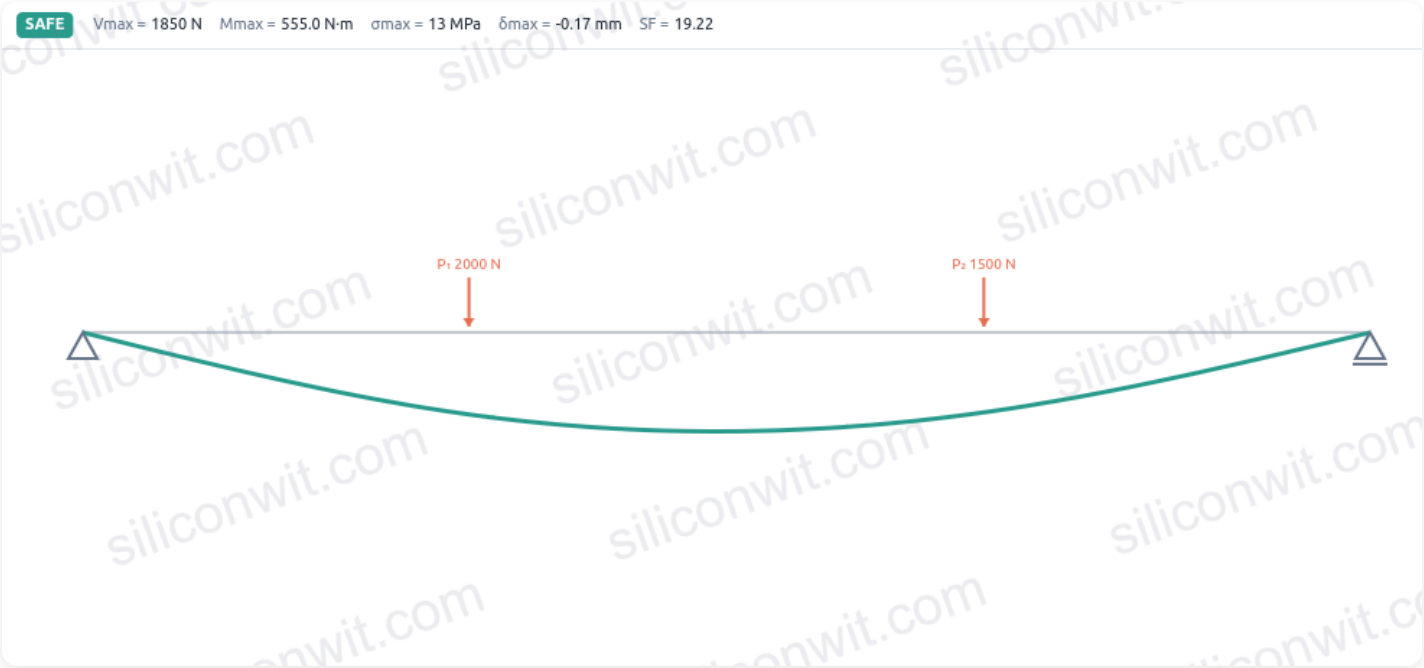
Lesson 2.5: Composite and Built-up Beam Systems



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A CNC machine bed built from a single material is always a compromise: steel is stiff but heavy, aluminum is light but deflects more. Bonding or bolting two materials together gives you the best of both, but the standard flexural formula no longer applies because each material has a different elastic modulus and carries a different share of the bending stress. The transformed section method resolves this by converting the

composite cross-section into an equivalent single-material section, letting you reuse the same bending equations you already know. In this lesson you will analyze a hybrid aluminum-steel CNC machine bed, locate the shifted neutral axis, and calculate the true stress in each material. #CompositeBeams #TransformedSection #CNCDesign

Learning Objectives

By the end of this lesson, you will be able to:

1. **Analyze** composite beams made of different materials using the transformed section method
2. **Locate** the neutral axis in composite beam cross-sections
3. **Calculate** bending stresses in each material of a composite system
4. **Design** hybrid structures for optimal strength-to-weight performance

> **Try it as you read**
>
> This lesson pairs with the Beam Analysis Simulator: vary the beam section and loading to see how the bending stress and deflection respond, the same response that drives the built-up and composite sections here. The Beam Analysis Experiments reproduce the worked examples step by step with Python.

Real-World System Problem: CNC Machine Bed Structure

High-precision CNC machines require extremely rigid bed structures to maintain accuracy during cutting operations. Modern CNC beds often use composite construction - combining steel reinforcement with aluminum casting to achieve optimal stiffness, weight, and thermal stability while managing cost.

System Description

CNC Machine Bed Components:

- **Steel Reinforcement Beams** (high stiffness backbone structure)
- **Aluminum Casting** (lightweight material filling and mounting surfaces)
- **Composite Cross-Section** (steel beams encased in aluminum)
- **Precision Ways** (guided surfaces for machine tools)
- **Vibration Damping** (integrated damping materials)

The Composite Challenge

During machining operations, the CNC bed experiences:

> ⓘ **Critical Loading Conditions**
>
> - **Heavy cutting forces** transmitted through the tool and workpiece
> - **Dynamic loads** from rapid axis movements and accelerations
> - **Thermal gradients** from machining heat and environmental changes
> - **Vibration loads** that must be damped to maintain surface finish
> - **Long-term creep** under sustained loads

> **Engineering Question:** How do we analyze the stress distribution in a composite CNC bed where steel reinforcement beams are encased in aluminum, and how do we ensure both materials work together effectively under bending loads?

Why Composite Beam Analysis Matters

Consequences of Poor Composite Design:

- **Interfacial failure** between steel and aluminum layers
- **Uneven stress distribution** leading to premature failure
- **Excessive deflection** reducing machining accuracy
- **Thermal stress cracking** from differential expansion

Benefits of Proper Composite Analysis:

- **Optimized material usage** leveraging each material's strengths
- **Predictable load sharing** between different materials
- **Enhanced structural performance** compared to single materials
- **Cost-effective design** balancing performance and economics

Fundamental Theory: Composite Beam Mechanics

Basic Composite Beam Assumptions

For composite beams with **perfect bonding** between materials:

1. **Plane sections remain plane** during bending
2. **No slip occurs** at material interfaces
3. **Strain is continuous** across the cross-section
4. **Each material follows** its own stress-strain relationship

The Transformed Section Method

Since different materials have different elastic moduli, we transform the composite section into an equivalent single-material section:

🔄 Transformation Ratio Formula

$$n = \frac{E_2}{E_1}$$

Where:

- n = Transformation ratio (dimensionless)
- E_2 = Elastic modulus of material to be transformed
- E_1 = Elastic modulus of reference material

Physical Meaning: The transformation ratio allows us to convert a composite beam into an equivalent single-material beam by adjusting the width of one material based on stiffness differences.

Transformation Strategy

Transform stiffer material to softer: If steel (E = 200 GPa) and aluminum (E = 70 GPa): $n = \frac{E_{steel}}{E_{aluminum}} = \frac{200}{70} = 2.86$

The steel section is replaced by an aluminum section **2.86 times wider**.

Composite Beam Analysis Steps

Step 1: Transform	Step 2: Locate Neutral Axis	Step 3: Calculate Properties	Step 4: Find Stresses

Transform one material to the reference material:

- Choose reference material (usually softer)
- Calculate transformation ratio n = E_2/E_1
- Transform width: $b_{2,transformed} = n \times b_{2,actual}$

Application: CNC Bed Composite Beam Analysis

Let’s analyze a realistic CNC bed cross-section step by step.

> **Problem Statement**
>
> **Hybrid CNC Machine Bed Composite Beam Analysis**
>
> **What we need to determine:**
>
> 1. **Transformation ratio** between steel and aluminum materials
> 2. **Neutral axis location** of the composite cross-section
> 3. **Maximum bending stresses** in both steel and aluminum regions
> 4. **Safety factors** and design adequacy for both materials
>
> **Key Question:** How do stresses distribute in a hybrid CNC bed with steel I-beam reinforcement encased in aluminum casting under a 50 kN distributed load?

Explore how the section drives the bending stress and deflection in the simulator:

Open the Beam Analysis Simulator

System Parameters:

- Hybrid CNC machine bed (steel I-beam reinforcement in aluminum casting)
- **Steel I-beam:** 150 mm × 200 mm × 12 mm flanges, 8 mm web, E_1 = 200 GPa, σ_yield = 250 MPa
- **Aluminum casting:** 300 mm wide × 250 mm tall, E_2 = 70 GPa, σ_yield = 140 MPa
- Span length: 2000 mm (simply supported)
- Applied load: `w` = 50 kN uniform distributed load
- `Safety factor`: 2.0

Step 1: Calculate Transformation Ratio

> **Click to reveal transformation ratio calculations**

Step 2: Locate Neutral Axis of Transformed Section

> **Click to reveal neutral axis calculations**

Step 3: Calculate Maximum Bending Moment and Stresses

> **Click to reveal bending moment and stress calculations**

Step 4: Calculate Stresses and Safety Factors

> **Click to reveal stress and safety factor calculations**

Engineering Problems

Problem 1: Steel-Concrete Composite Beam

A composite beam consists of a steel I-beam with a concrete slab cast on top, used in building construction.

Given:

- Steel I-beam: W200×36 ($A = 4580$ mm², $I = 40.5 \times 10^6$ mm⁴, centroid 100 mm from bottom)
- Concrete slab: 1000 mm wide × 100 mm thick, cast on steel top flange
- Simply supported span: $L = 6000$ mm
- Uniform load: $w = 15$ kN/m (including self-weight)
- Materials: Steel $E_1 = 200$ GPa, Concrete $E_2 = 25$ GPa
- Perfect bond assumed between steel and concrete

Find: Maximum stresses in both steel and concrete.

> **Click to reveal solution**

Problem 2: Aluminum-Steel Hybrid Beam

A lightweight beam combines aluminum flanges with a steel web for optimal strength-to-weight ratio in aerospace applications.

Given:

- Steel web: 200 mm high × 8 mm thick ($E_1 = 200$ GPa)
- Aluminum flanges: 150 mm wide × 20 mm thick, top and bottom ($E_2 = 70$ GPa)
- Cantilever beam length: $L = 1200$ mm
- Point load: $P = 5000$ N at free end
- Perfect bonding between materials

Find: Maximum bending stresses in steel and aluminum components.

> **Click to reveal solution**

Problem 3: Carbon Fiber-Aluminum Composite Beam

A high-performance beam uses carbon fiber reinforcement bonded to aluminum structure for maximum stiffness with minimal weight.

Given:

- Aluminum beam: rectangular 60 mm wide × 80 mm thick ($E_1 = 70$ GPa)

- Carbon fiber strips: 60 mm wide × 3 mm thick, bonded to top and bottom (E_2 = 150 GPa)
- Simply supported span: L = 800 mm
- Uniform distributed load: w = 2000 N/m
- Perfect bond between materials

Find: Stress distribution and maximum stresses in each material.

> **Click to reveal solution**

> **Instrument it**
>
> A built-up beam hides how its two materials share the bending load until you measure it. Bond a strain gauge to each material at the same height above the neutral axis; the strains match where the materials are bonded, while the stresses jump by the modulus ratio, exactly what the transformed-section method predicts. Read both gauges with an ESP32 or STM32 and you can confirm the load split on siliconwit.io and check that the stiffer material carries its designed share.

Summary and Next Steps

In this lesson, you learned to:

1. **Apply** the transformed section method to analyze composite beams
2. **Calculate** stress distribution in multi-material systems
3. **Consider** interface requirements and thermal effects
4. **Design** composite structures for optimal performance

Key Design Insights:

- Transformed section method handles different E values
- Stiffer materials carry proportionally more stress
- Interface bond strength is critical for composite action

Critical Formula: $\sigma_2 = n \times \sigma_1$ where $n = \frac{E_2}{E_1}$

Coming Next: In Lesson 2.6, we'll analyze principal stresses and failure criteria for critical stress evaluation in mechatronic joint design using Mohr's circle analysis.

Comments

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