Definition of Criteria for Maximizing the Structural Performance of Steel Profiles for Cellular Beams via Monte Carlo Simulation

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Abstract. Cellular beams (CB) differ from solid web beams (SWB) due to the openings in their web and exhibit unique resistance mechanisms, including complex internal forces such as normal forces, shear forces, and bending moments, all distributed in a peculiar manner across their sections. Their complex geometry causes the resistance mechanisms to depend on various parameters or geometric relationships, making the design process less intuitive compared to conventional beams. Furthermore, the critical section is not always related to the most heavily loaded section, contrary to the behavior observed in SWBs. To correlate the geometric characteristics of the profiles and the cutting parameters of the openings across various span ranges, a Monte Carlo simulation was carried out, allowing for the establishment of optimal ranges for input data and ranking of the most sensitive parameters. Among the insights obtained, the inadequacy of I-section profiles specified by ABNT standards stands out, as their characteristics negatively impact the structural efficiency of CBs, as well as counterintuitive behaviors related to the variation of section and web opening dimensions. The study culminated in the formulation of guidelines for solving design problems in CBs and resulted in solutions with lower steel consumption compared to conventional profiles. Based on the analyses performed, a catalog of custom welded I-section profiles was developed specifically for use in cellular beams.

Keywords: cellular beams, structural efficiency, Monte Carlo simulation, geometric parameters.

Introduction

Cellular beams (CBs), defined as expanded steel sections with circular web openings, represent an advanced structural solution offering significant design and construction advantages over solid web beams (SWBs) [1]. Web openings inherently increase the depth-to-weight ratio, as well as elastic and plastic section modules (S and Z), and moment of inertia (I_x), enabling potential cost savings in long-span applications. Furthermore, web openings allow for the integration of building installations, such as HVAC ducts and conduits, thereby optimizing vertical space within floor systems [2].

However, the geometric complexity introduced by web openings impacts the structural behavior of cellular beams. Unlike solid web members, CBs cannot be designed with simple analytical methods, as the web openings introduce numerous additional failure modes that are not present in solid web members, making their design process less intuitive [3]. An important observation is that for cellular beams, the critical sections are not always coincident with the sections subjected to the maximum internal loadings, a behavior contrary to that observed in SWBs. This phenomenon arises from the complex interaction of axial and shear forces within the tee-sections and web posts that form the openings, leading to stress concentrations. Research indicates that cellular beams behave similarly to Vierendeel trusses, with design theories primarily developed from experimental and numerical studies [4].

Initial observations during the development of a Cellular Beam Manual for ArcelorMittal Brazil in 2024 [5] highlighted several non-intuitive aspects in CB design, particularly concerning the selection of the original profile and cutting geometry. Moreover, existing I-section profiles, commonly available in catalogs and national standards, are unsuitable for optimal structural efficiency when converted into cellular beams. Their predefined geometric ratios, such as flange slenderness (d/b_f) and web slenderness (h/t_w), can negatively impact the performance of cellular beams.

This paper presents a methodology for defining optimal geometric parameters for welded I-section profiles for cellular beam applications and ranking of the most sensitive parameters. The optimization was achieved through a Monte Carlo simulation, which identified the most suitable ranges for design variables and developed a catalog of custom-welded I-section profiles (VCS) tailored explicitly for cellular beam design. This catalog aims to overcome the limitations of standard profiles and provide optimized solutions that lead to lower steel consumption in construction. Finally, the study culminated in the formulation of guidelines for solving design problems in CBs.

The design problem

During the development of a Cellular Beam Manual for ArcelorMittal Brazil in 2024, the authors first attempt was to design CBs welded I-sections from the VS (welded beams) series specified by the Brazilian standard ABNT NBR 5884:2013 [6]. After developing a few validation examples, the authors noted that the designed CBs were much heavier than expected, making the CB solution economically unattractive when compared with SWBs. Moreover, the CBs were failing in the ULS checks for loads smaller than the ones expected for SWBs with the same original I-profile, especially due to failure on the T-sections at the openings. Finally, to improve the CB resistance, the authors attempt to increase the T-section resistance by reducing the opening diameter, to gain mass in those sections. However, in many cases, increasing the T-section only made the CB performance worse, which was something not intuitive for the authors.

The ultimate limit state design of cellular beams involves analyzing the monosymmetric T-section resistance above and below the openings, as well as the web post stability between them [3], [7], [8]. Hence, the ultimate resistance of CBs depends on the geometric properties of the original I-profile, the cutting parameters, and the resulting CB dimensions (Figure 1).

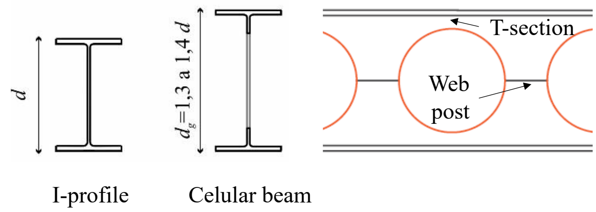


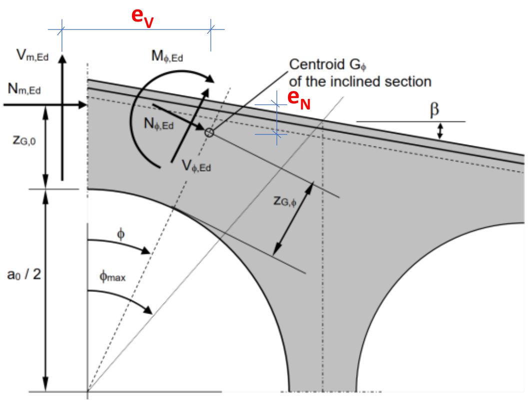
Figure 1. Geometric characteristics of a cellular beam (d is the original profile height and d_g is the CB height).

Unlike solid web beams, the relationship between geometric parameters and solicitation rates in CBs is not intuitive. This is especially true for selecting the original profile and determining cutting geometry, as the critical section in a CB isn't necessarily where the maximum internal forces occur. Furthermore, shear and normal forces in the T-sections are eccentric to the inclined planes within the opening diameter (a_0), leading to bending moments and normal forces that change with the inclined plane's angle (Figure 2). Moreover, the critical section in the web posts depends on the distance between openings, the CB height, and the rate of the opening diameter. Therefore, the critical section depends on the resulting internal forces on each inclined T-section at each opening and the T-section geometry itself.

The CB T-section geometry inherits the flange width (b_f), thickness (t_f), and slenderness (b_f/t_f), and the web thickness (t_w) from the original I-profile. However, the T-section web height (h) and slenderness (h/t_w) are inversely proportional to the ratio between the opening diameter and the original profile height (a_0/d), as shown in Figure 3. If the T-section is under traction and shear force, increasing its area by reducing the opening diameter will always improve the section's ultimate resistance. On the other hand, if the T-section is under compression, or if the resulting bending moment compresses the T-section web, the relationship between its ultimate resistance and the ratio a_0/d is not straightforward.

Reducing the opening diameter increases the T-section area and its mechanical properties, and improves its resistance to shear force, positive normal force, and bending moment compressing the flange. However, when the

T-section is subjected to a compressive normal force or the bending moment compresses the web, reducing the opening diameter may result in T-sections with slender webs. Therefore, in cases where reducing the opening diameter does not result in a slender T-section web, the engineer will observe an overall increase in the T-section's ultimate resistance. At the same time, if the opening diameter reduction reaches a point where the T-section web becomes too slender with elastic behavior, the engineer will experience a sudden drop in the T-section ultimate resistances associated with the compression of the slender T-section web [9].



T-section:
- $V_{m,Ed}$ shear force
- $N_{m,Ed}$ axial compression force
- $z_{G,0}$ distance from the centroid to opening
- a_0 opening diameter

Inclined T-section:
- ϕ inclination angle
- $V_{\phi,Ed}$ shear force
- $N_{\phi,Ed}$ axial compression force
- $z_{G,\phi}$ distance from the centroid to opening
- e_V $V_{m,Ed}$ eccentricity
- e_N $N_{m,Ed}$ eccentricity

Figure 2. T-section internal forces.

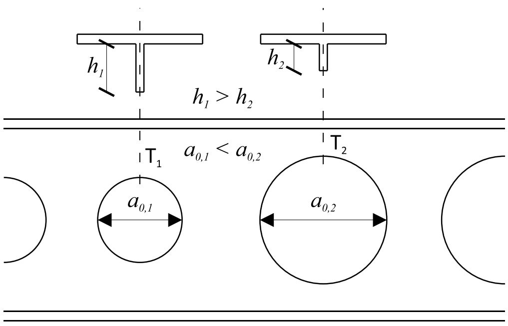


Figure 3. Relationship between the opening's diameter and the T-section height.

The I-profiles within the VS series were initially designed for SWBs. Therefore, their flange and web dimensions are optimized for plastic or elastic-plastic behavior under bending moment and shear force. However, a critical issue arises when the VS series I-profiles are used as the base for CBs. The stability of the T-sections under compression becomes paramount, with the T-section flange and web slenderness facing harsher limits in CB design. For instance, while all I-profile flanges in the VS series exhibit plastic or elastic-plastic behavior under bending moments (as intended for SWBs), only about 40% of these same I-profiles would maintain this behavior for the T-sections of CBs under compression, as shown in Table 1.

Table 1. VS series for welded I-profiles: flange behavior for SWBs and CBs application.

VS series (welded I-profiles) application *	Flange behavior	
	Plastic or elastic-plastic	Elastic
Solid web beams	100%	0%
Cellular beams	40%	60%

* For steel grade ASTM A572 G50.

Moreover, the VS series is set to keep the web slenderness at the boundary between elastic-plastic and elastic behavior; only 4% of these I-profiles have slender webs with elastic behavior. Consequently, when CBs are fabricated from these I-profiles, their T-section webs are highly susceptible to reaching their slenderness limit for elastic behavior under compression, even with relatively small heights due to their inherent thinness. Therefore, increasing the opening diameter reduces the T-section area, eventually reaching its ultimate resistance. Conversely, reducing the opening diameter can lead to a slender web, making it prone to instability failure under compression.

Methodology

The methodology employed for this study centered around a Monte Carlo simulation to define optimal geometric characteristics for cellular beam profiles, as well as their cutting parameters and the ranking of the most sensitive parameters. The process was structured as shown in Figure 4.

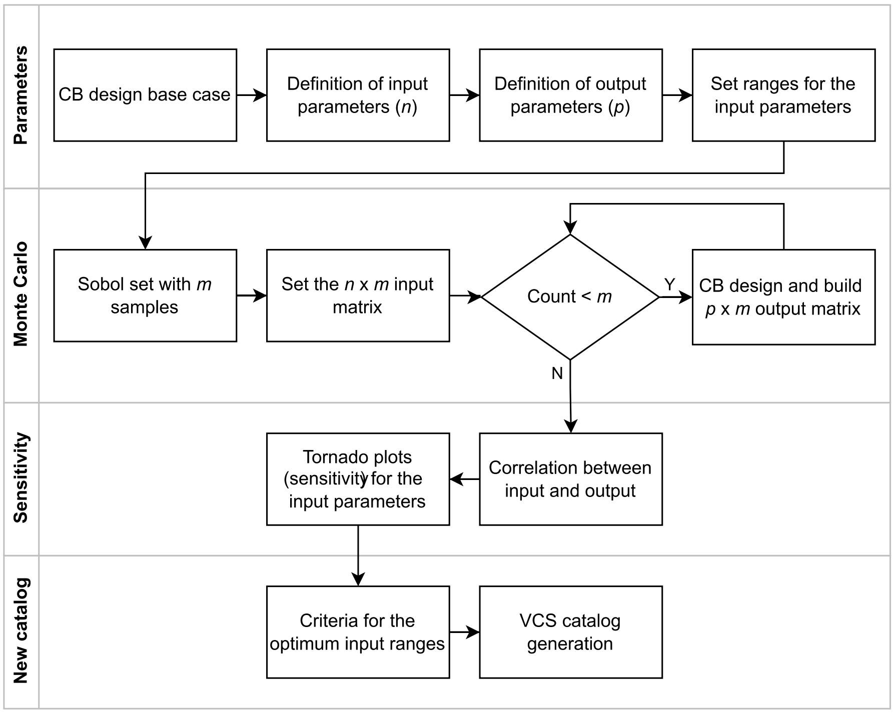


Figure 4. Methodology's flowchart.

The CB reference design case was selected from Example 1 of the VCA+ Software's Manual from ArcelorMittal [5], [10], [11] and its main fixed properties are detailed in Table 2. The corresponding six input parameters (n) and their ranges can be found in Table 3, and the eight output parameters (p) are presented in Table 4.

For this study, the Monte Carlo simulation was developed in Matlab. The process began with the generation of a quasirandom Sobol sequence, configured to skip (omit) the first 10^6 points (skip) and leap over 2^{32} points for every point taken. The Sobol sequence was then scrambled using a Matousek-Affine-Owen algorithm. Finally, the first 10^6 points (m) to create the 6 by 10^6 input matrix ($n \times m$).

The CB design was implemented in Matlab, replicating the exact procedures of the developed VCA+ software [11]. All 10^6 design cases were then simulated and their output parameters recorded. Subsequently, a sensitivity analysis was performed to quantify how input parameters influenced the output results. This was achieved by calculating the linear correlation coefficient between each input and output, then ranking the input parameters from most to least significant for each output using a tornado plot.

Finally, the insights gained from the sensitivity analysis were used to develop a series of custom welded I-section profiles (designated as VCS) specifically tailored for cellular beam applications, and a guideline for solving design problems in CBs.

Table 2. Main properties for the reference design case.

Property	Value
Horizontal span	8 meters
Free lateral displacement length	4 meters
Beam constraints	Simply supported
Beam type	Intermediate
Floor spacing	4 meters (on each side)
Steel grade	ASTM A572 Gr. 50
Permanent loads	
Self-weight	Calculated
Surface load	1,00 kN/m^2
Live load	
Q1	5,30 kN/m
Q2	1,00 kN/m

Table 3. Input parameters (refer to Figure 5 for the variables explanation).

Pos.	Description	Parameter	Range
1	Ratio between the original I-profile's height and flange width	d/b_f	1,5 to 3,0
2	Original I-profile flange slenderness	$b_f/(2\ t_f)$	7,5 to 11
3	Original I-profile web slenderness	h/t_w	40 to 100
4	Ratio between the opening diameter and the original I-profile height	a_0/d	0,75 to 1,1
5	Ratio between the openings spacing and diameter	d/a_0	1,1 to 1,7
6	Expansion rate	H_t/d	1,2 to 1,5

Table 4. Output parameters.

Pos.	Description	Parameter	Criteria
1	Mass of the original solid web I-profile	kg	n/a
2	Highest loading ratio obtained in the design	S_d/R_d	$\leq 1{,}0$
3	Loading ratio of normal force in the upper chord *	N_{Sd}/N_{Rd}	$\leq 1{,}0$
4	Loading ratio of shear force in the upper chord *	V_{Sd}/V_{Rd}	$\leq 1{,}0$
5	Loading ratio of bending moment in the upper chord *	M_{Sd}/M_{Rd}	$\leq 1{,}0$
6	Loading ratio of combined N+M forces in the upper chord *	MN_{Sd}/MN_{Rd}	$\leq 1{,}0$
7	Loading ratio of horizontal shear in the web post	V_h	$\leq 1{,}0$
8	Loading ratio of web post buckling	V_b	$\leq 1{,}0$

* Highest loading ratio obtained for all inclined T-sections.

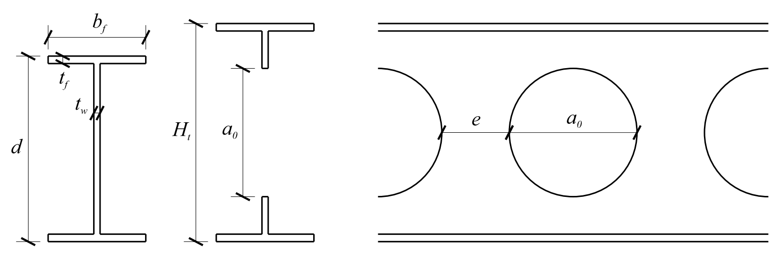


Figure 5. Original I-profile and cellular beam dimensions.

Results and discussion

The Monte Carlo simulation and subsequent sensitivity analysis yielded crucial insights into the optimal geometric characteristics for cellular beams.

As depicted in Figure 6, the tornado plot visualizes the outcomes of the sensitivity analysis. Input parameters are ordered by significance on the vertical axis, decreasing from top to bottom. Their respective correlations with each output parameter are represented by bars along the horizontal axis. The magnitude of a bar directly reflects the strength of the input's influence on a given output. Furthermore, positive correlations denote a direct proportionality between input and output changes, whereas negative correlations signify an inverse proportionality.

Notably, the two most significant input parameters are related to the original I-profile geometry: the ratios d/b_f and h/t_w. These are followed by three inputs associated with the CB cutting properties (a_0/d, e/a_0, and k), with the original I-profile flange slenderness ($b_f/t_f/2$) being the least significant.

Given that the d/b_f ratio is the most significant input parameter, a cloud point was generated of the total mass for each simulated design case against its respective d/b_f ratio, as presented in Figure 7. The plot clearly illustrates an inverse proportionality between mass and the d/b_f ratio. Mass-optimized solutions are observed within the d/b_f range of 2.5 to 3.0. Nevertheless, most I-profiles available in the standard VS catalog for CB applications are limited to the 2.0 to 2.5 range. Therefore, the d/b_f range of 2.5 to 3.0 was selected for the custom VCS catalog.

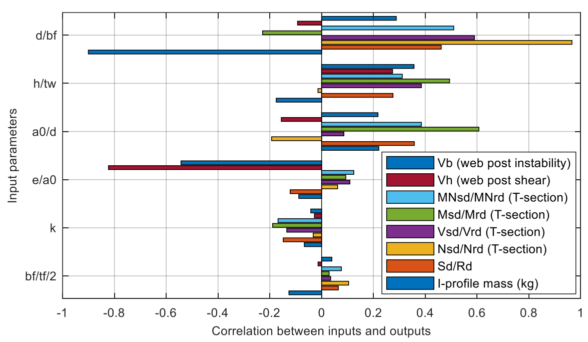


Figure 6. Mass (kg) versus d/b_f for all simulated design cases.

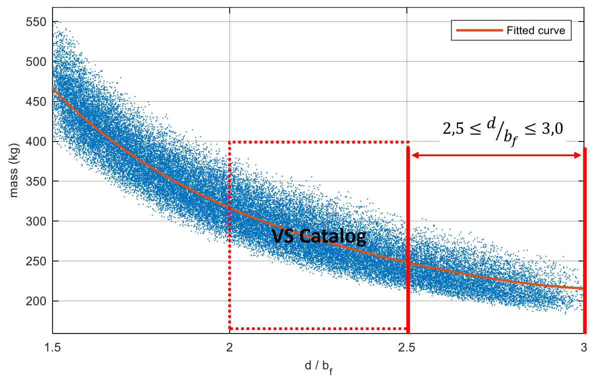
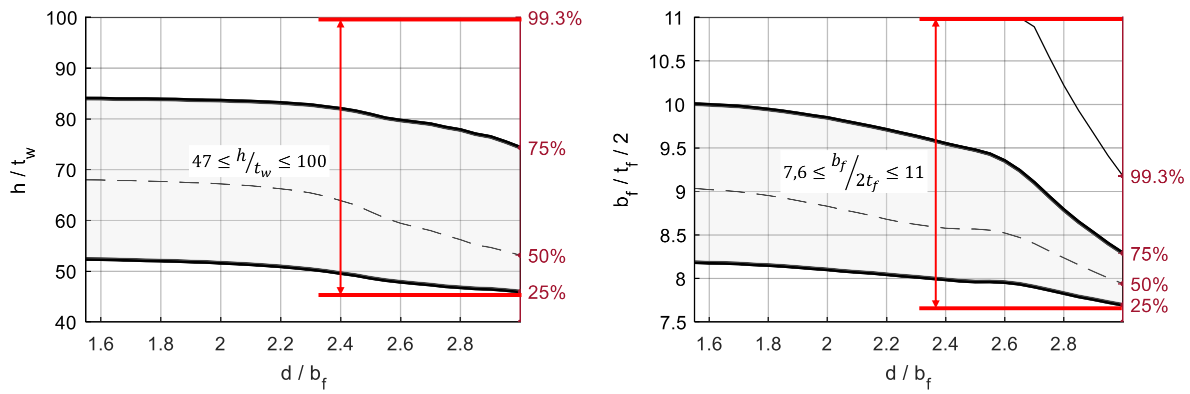


Figure 7. Mass (kg) versus d/b_f for all simulated design cases.

Furthermore, the inputs h/t_w and $b_f/t_f/2$ were plotted against the d/b_f ratio in Figure 8, but this time as lines showing the interquartile range and the maximum and minimum percentiles. The criteria for selecting the input ranges for the custom VCS catalog were as follows: the first quartile (25%) value for $d/b_f = 3.0$ and the maximum quartile (99.3%) value for $d/b_f = 2.5$.



(a) h/t_w versus d/b_f (b) $b_f/t_f/2$ versus d/b_f

Figure 8. Range definition for h/t_w and $b_f/t_f/2$.

Table 5 shows the criteria for designing the custom VCS series for CB applications. Based on those criteria, 113 welded I-profiles with height ranging from 300 to 1000 mm were generated. The starting and ending I-profiles from the custom VCS catalog are shown in Figure 9.

Comparative analyses using the VCA+ software [11] demonstrated significant benefits. For instance, replacing a standard VS 600x111 profile with a VCS 600x85 profile resulted in a 23% reduction in mass, while still meeting all Ultimate Limit State (ULS) and Serviceability Limit State (SLS) criteria. Similarly, a VCS 550x63 profile proved to be 29% lighter than a VS 550x88. Overall, by utilizing optimal VCS profiles, solutions with lower steel consumption of up to 43% were achieved compared to conventional profiles, proving the efficacy of the proposed custom profiles in enhancing both structural efficiency and economic viability. This demonstrates a substantial direct material cost saving and a reduction in the overall mass of the structure.

Table 5. Design criteria for the custom VCS series.

Criterion 1	$2{,}5 \leq d/b_f \leq 3{,}0$
Criterion 2	$47 \leq h/t_w \leq 100$
Criterion 3	$7{,}6 \leq b_f/(2\,t_f) \leq 11$

Designação	d (mm)	b_f (mm)	t_f (mm)	t_w (mm)	massa (kg/m)
VCS 300x22,6	300	120	6,3	4,75	22,6
VCS 300x28,2	300	140	8	4,75	28,2
VCS 350x24,5	350	120	6,3	4,75	24,5
VCS 350x28,6	350	120	6,3	6,3	28,6
VCS 350x30	350	140	8	4,75	30
VCS 350x34,1	350	140	8	6,3	34,1
VCS 350x32,6	350	160	8	4,75	32,6
VCS 350x36,6	350	160	8	6,3	36,6
VCS 400x31,9	400	140	8	4,75	31,9
VCS 400x36,6	400	140	8	6,3	36,6
⋮					
VCS 950x291,2	950	400	25	19	291,2
VCS 1000x182,9	1000	350	16	12,5	182,9
VCS 1000x209,5	1000	350	16	16	209,5
VCS 1000x232,3	1000	350	16	19	232,3
VCS 1000x250,2	1000	400	25	12,5	250,2
VCS 1000x276,3	1000	400	25	16	276,3
VCS 1000x298,7	1000	400	25	19	298,7
VCS 1000x269,8	1000	450	25	12,5	269,8
VCS 1000x295,9	1000	450	25	16	295,9
VCS 1000x318,3	1000	450	25	19	318,3

Figure 9. Excerpt from the VCS catalog.

Conclusion

This research addresses the challenge of designing efficient cellular beams by introducing a series of custom welded I-section profiles (VCS), specifically optimized for their unique structural behavior. The study employed a Monte Carlo simulation to analyze the sensitivity of various geometric parameters and define their optimal ranges, a critical step given the counterintuitive behaviors observed in cellular beams compared to solid web beams.

The findings demonstrate that standard I-section profiles are often geometrically inadequate for optimal cellular beam design, exhibiting suboptimal ratios of d/b_f and h/t_w. The new VCS series, comprising profiles designed within the identified optimal ranges, facilitates the selection of root beams that are inherently more suited for the complex resistance mechanisms and limit states governing cellular beam design, including Vierendeel bending and web post buckling.

The practical application of these optimized profiles, as demonstrated through comparative analyses, shows significant potential for lower steel consumption and enhanced structural performance, with savings up to 43% in steel mass. This not only contributes to material efficiency but also supports more sustainable and cost-effective construction practices. The developed guidelines and the VCS catalog, supported by advanced analytical tools like the VCA+ software, provide engineers with a robust framework for a more intuitive and optimized design process for cellular beams, maximizing their inherent advantages in modern construction.

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