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Enhancing plate girder shear performance using low-frequency sinusoidal webs

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Abstract
Thin plates in shear are used in many applications such as the webs of steel plate girders, shear walls, ships, and aircraft and are typically designed to maximize plate depth and minimize plate thickness. However, the capacity of slender plates is limited by shear buckling. Conventional solutions to shear buckling include welded transverse stiffeners or corrugated plate shaping, but these strategies introduce the potential for fatigue cracking and fabrication challenges, respectively. Alternatively, the authors propose forming low-frequency sinusoidal (LFS) patterns along the plate's longitudinal axis as a novel, less fabrication-intensive approach to enhancing the shear capacity of thin plates. The low frequencies utilized in this study are much lower than those used in commercial corrugated products and previous research, resulting in lower forming stresses and potentially improved fatigue behavior. Experimentally validated finite element models are used to parametrically evaluate the effects of sinusoidal frequency and initial geometric imperfection. Measurements of elastic shear buckling load, ultimate shear load, and shear yielding are used to evaluate the effects of the parameters. The results show that significant increases in shear strength and material efficiency can be achieved using an LFS approach. LFS plates combine durability, material efficiency and ease of fabrication in a strategy that can benefit the industry.

1. Introduction

Slender plate girder design is often governed by web shear buckling capacity (Timoshenko and Gere 1961; Lee et al. 1996). To resist web shear buckling, transverse (vertical) stiffeners are often welded onto the web plates at regular intervals to restrain lateral displacement at the panel boundaries (Bleich 1952; Kim and White 2014). The space between vertical stiffeners is equal to "*a*" and defines the "panel." Stiffeners increase a web plate's shear buckling load, V_{cr}, by restraining out-of-plane displacement and reducing web panel aspect ratios to a/D, where D equals the web depth (Bleich 1952). However, welded stiffeners have high labor costs and are sensitive to fatigue (Balaji Rao et al. 2013; Skaloud 2013). Therefore, strategies to reduce the use of transverse stiffeners would be beneficial to both girder construction cost and longevity.

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Corrugated plates are an alternative to transverse stiffeners (Riahi et al. 2018), and they increase out-of-plane stiffness, thus increasing the web's shear buckling load (Kim and White 2014; Pasternak and Kubieniec 2010). Sinusoidally corrugated web plates have demonstrated longer fatigue life than both stiffener-stiffened plates and trapezoidal corrugated webs (Ibrahim and El-Dakhakhni 2006; Harrison 1965; Chen et al. 2013). This is because the smooth, continuous curvature in sinusoidally corrugated plates produces lower forming stresses and fewer stress concentrations than the sharp bend radii in trapezoidal corrugated webs (Ibrahim and El-Dakhakhni 2006; Chen et al. 2013). The disadvantage to corrugated plates is the increased fabrication difficulty both in forming the plate and making the flange-to-web plate welds. Fabrication is achieved via an automated process whereby the web plate is cold-formed and then robotically welded to the flanges, as described by (Pasternak and Kubieniec 2010; Siokola 1997). The technique has implicit limits on plate girder depth and web plate thickness; the maximum sinusoidal web depth is 1.5 m, while the maximum sinusoidal web thickness is 6 mm (Pasternak and Kubieniec 2010).

This paper proposes an alternative web plate shape to increase the shear buckling strength of plate girders by introducing low-frequency sinusoids (LFS). "Low-frequency" denotes sinusoids with a full wavelength on the order of 0.7 m or longer. In comparison, commercial sinusoidal corrugated web plates typically have a full wavelength of 0.155 m (Pasternak and Kubieniec 2010), as shown in Fig. 1. The proposed frequencies are thus much lower than those used in commercial corrugated web products and in previous research studies (Pasternak and Kubieniec 2010; Chen et al. 2013). This paper presents the performance of low-frequency sinusoids (LFS) plate girders and compares their performance to plate girder counterparts with flat webs and corrugated webs.

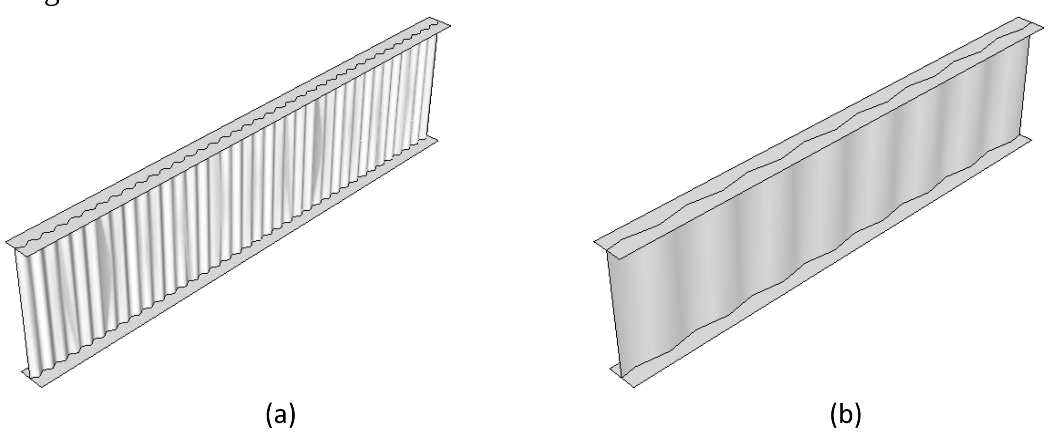

Figure 1: Representative plate girders with a (a) typical corrugated web and (b) LFS web

2. Modeling approach

A nonlinear finite element (FE) study was conducted using ABAQUS 2017 to analyze the behavior of several LFS web girder designs under pure shear (Dassault Systemes 2017). Web panels with flanges were modeled with the boundary conditions and loading shown in Fig. 2. Uniformly distributed shear loads are applied along the four edges of the web plate. The load at the top and bottom of the web follows the shape of the sinusoid at its points of application. The LFS geometries were modeled without considering any resulting forming stresses.

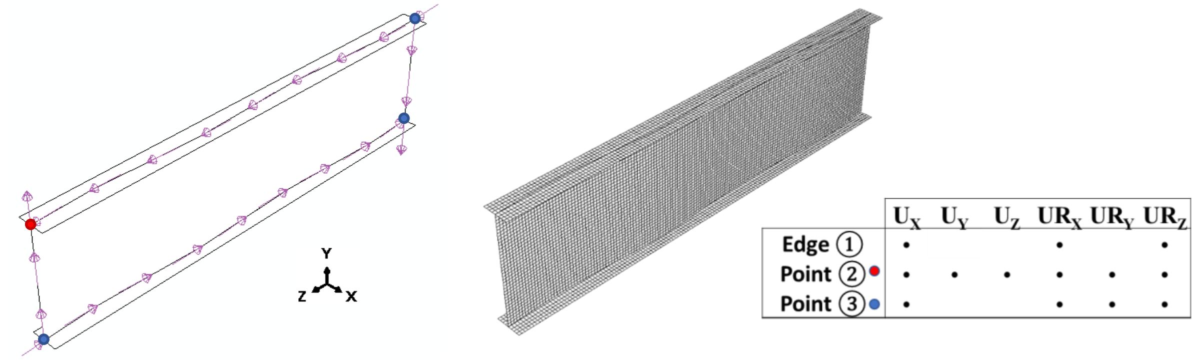

Figure 2. Boundary conditions and pure shear loading on a representative LFS specimen with f_n = 1 (left), including finite element mesh with 4 cm mesh size (right). U denotes displacement, and UR denotes rotation.

The steel material model used for this study has an elastic modulus E=200 GPa, yield stress F_y=345 MPa, and Poisson's ratio ν=0.3. The steel is modeled as elastoplastic with strain-hardening defined by the Eurocode 3, Part 1-2 (CEN 2001). ABAQUS element type S4 ("doubly-curved, general purpose, finite membrane strains") (Dassault Systemes 2017) are utilized with five integration points through the plate thickness (Garlock et al. 2019; Wang et al. 2019). The FE mesh has a 4 cm maximum edge dimension (see Fig. 2), as determined by a previous convergence study on the elastic buckling load of a flat web panel (Wang et al. 2019).

The elastic shear buckling load (V_{cr}) and buckled eigenmode shapes are determined via a linear eigenvalue analysis. For the nonlinear analysis procedure, an initial geometric imperfection is applied to the web by overlaying a scaled value of the first shear buckling eigenmode geometry onto its finite element mesh. The maximum magnitude of this initial imperfection is one of the parameters of this study: D/10,000, D/1000, D/400, and D/100 (Wang et al. 2019). The smallest value (D/10,000) represents a negligible initial imperfection that still allows buckling to occur numerically in the finite element model, while D/1000 and D/400 represent more realistic imperfections per previous experimental measurements (Moon et al. 2009; Driver et al. 2006; Pasternak 2004; Gomez 2020) and D/100 represents the largest initial imperfection within industry tolerance for flat webs per the D1.5M/D1.5 Bridge Welding Code (AASHTO/AWS 2010). Once initial imperfections are applied, each specimen is quasi-statically loaded (i.e. very slowly with negligible dynamic effect) to its ultimate shear load V_u using the Modified Riks nonlinear solver (Dassault Systemes 2017; Glassman et al. 2016). The ultimate shear load V_u was taken as the peak value in the shear load-displacement response (Glassman and Garlock 2016).

This nonlinear FE modeling approach has been previously validated for several flat web girder specimens using the results of experimental tests by others (Glassman and Garlock 2016) and has been validated for sinusoidal corrugated webs in the author's work (Wang et al. 2021).

3. Parametric Study of LFS Geometry

A parametric study was conducted to investigate the effect of sinusoidal frequency (wavelength) on web shear buckling behavior of a prototype girder, which is based on the *FHWA Standard Plans for Highway Bridges* (FHWA 1982) with a web depth D=1.473 m (58") and web thickness t_w=11mm (7/16") (resulting in web slenderness D/t_w=133). The top and bottom flanges both have width b_f = 356 mm (14") and thickness t_f=27 mm (1-1/16"). The web panel aspect ratio (a/D) is given by the length of the web panel *a* over the web depth *D*. A panel length of 5.892 m (19 ft, 4 in), resulting in an *a/D* ratio of 4, was used to model the case of an unstiffened web. This panel length is close to the distance between cross-bracing from (FHWA 1982), which is 6.858 m (22'-6"). In general, an "unstiffened" plate in the context of this paper refers to a panel aspect ratio (*a/D*) greater than 3. Unstiffened flat plates have postbuckling shear capacity per Höglund (Höglund 1997) and recently adapted by Daley et al. (Daley, Davis and White 2017) for the AISC specification (AISC 2016). Postbuckling shear capacity is characterized by the postbuckling reserve (defined as V_u- V_{cr}) (Yoo and Lee 2006).

The following parametric variations of the prototype girder are considered: normalized wave frequency (f_n) as shown in Fig. 3, and the magnitude of initial geometrical imperfections. Note that only the web plate is sinusoidal (and only in the longitudinal direction), while the flanges remain straight. The sinusoidal amplitude (*A*) in Fig. 3 is held constant at 3 cm. The authors have also extended this study to consider additional parameters such as amplitude, web depth, and web slenderness (Wang et al. 2021), the details of which are not provided here for brevity.

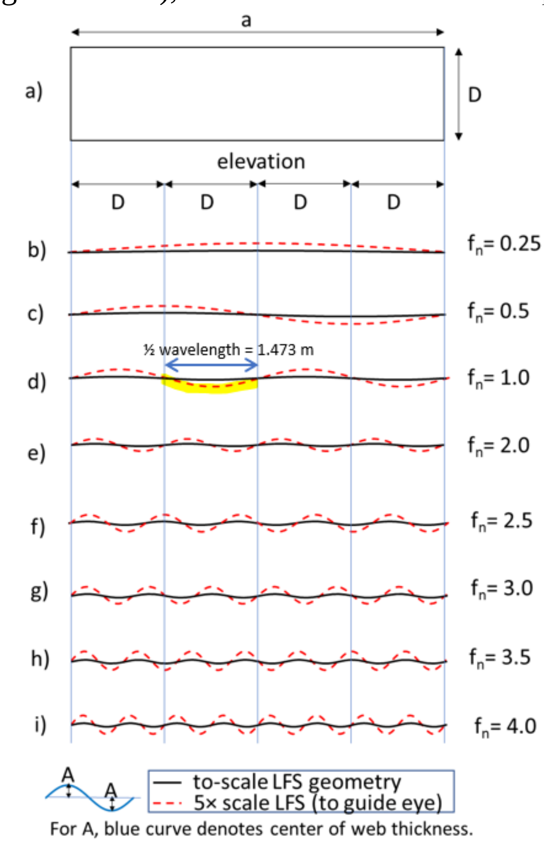

Figure 3. Low-Frequency Sinusoidal (LFS) web geometry: a) elevation, b) to i) various normalized wave frequencies (f_n) and amplitude (A).

Fig. 3 illustrates the wave frequencies that are considered for this paper. A normalized wave frequency (f_n) equal to 1.0 is defined as the wave pattern with one half sine wave over a distance of 1.473 m (i.e. the depth of the prototype web), as represented by Fig. 3(d). The minimum f_n was zero (corresponding to a flat plate) while the maximum f_n was set equal to 4.0 per Fig 3(i). Sinusoidal amplitude, *A*, measures the transverse distance from flange centerline to the web centerline at the peak of the sinusoid as shown in Fig 3. Table 1 introduces the low-frequency sinusoidal (LFS) web geometries that are considered in this study and lists their full wavelengths. The nomenclature of the girder specimens is expressed as F#-A3, with the first value representing the normalized wave frequency f_n and the second value representing the amplitude in centimeters (i.e. A=3 cm, see Fig. 3). In this study, the dimensions of the prototype used are the following unless otherwise noted: D=1.473 m, D/t_w=133, length of the girder panel 5.892 m [19'-4"], b_f=356 mm, t_f=27 mm.

Table 1: Parametric matrix of LFS frequency in the prototype girder.

Specimen Name	f_n (see Fig. 3)	**wavelength (m)**
Flat web	0	N/A
F0.25-A3	0.25	11.784
F0.5-A3	0.5	5.892
F1-A3	1	2.946
F1.5-A3	1.5	1.964
F2-A3	2	1.473
F2.5-A3 (baseline)	2.5	1.178
F3-A3	3	0.982
F3.5-A3	3.5	0.842
F4-A3	4	0.737

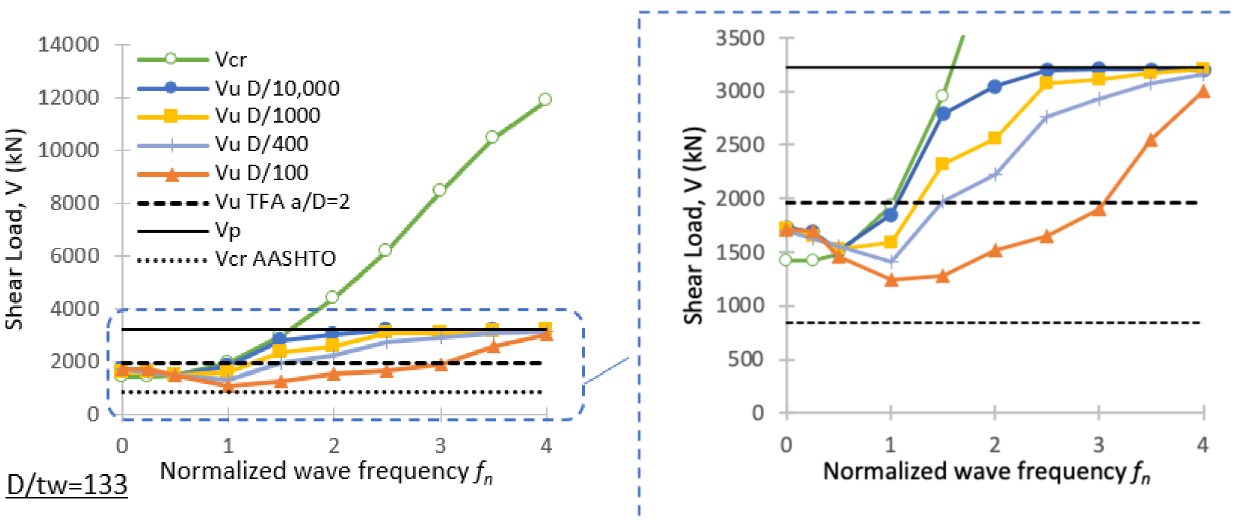

Figure 4. Variations of normalized wave frequency and initial imperfection magnitude (amplitude = 3cm, depth = 1.473 m, web slenderness = 133). Each f_n value corresponds to the specimen F[f_n]-A3. f_n=0 corresponds to the "Flat web" specimen.

Fig. 4 evaluates the effects of wave frequency and initial imperfection on V_{cr} and V_u. The black dotted line shows the AASHTO prediction for shear strength of the unstiffened flat web specimen (V_{cr} AASHTO), while the black solid line shows the plastic shear strength (V_p) of the flat web specimen. V_p is calculated using the von Mises yield criterion in Eq. 1:

$$V_p = 0.577\, F_y\, D\, t_w \tag{1}$$

To compare the strength of LFS webs to transversely stiffened webs, the black dashed line shows the AASHTO design capacity of a transversely stiffened a/D=2 panel based on Tension Field Action (TFA) theory. This value of a/D = 2 implies that a vertical stiffener is placed at the midlength of the flat web specimen (recall that the specimens studied here have a/D = 4 per Fig. 3).

Fig. 4 shows that V_{cr} grows dramatically with increasing wave frequency. Compared to the flat web girder (plotted as f_n=0), minimal benefit in V_{cr} is observed for f_n < 0.50; however, V_{cr} exceeds V_p for f_n slightly larger than 1.5. In these cases, elastic buckling is ideally avoided and the inelastic limit state of V_u is reached (Wang et al. 2019; White and Barker 2008). It is also seen that both initial imperfections and wave frequency affect V_u significantly and thus will affect the postbuckling reserve (defined as V_u- V_{cr}). For D/10,000 imperfection magnitude, the lower-frequency specimens (e.g. f_n=0, 0.25, and 0.5) show V_u as higher than $V_{cr,}$ and thus the plates have postbuckling reserve. For the intermediate frequencies tested (e.g. f_n=1.0 and 1.5), V_u is virtually identical to V_{cr}, with negligible postbuckling reserve. In contrast, for f_n=2 and above, V_u is lower than V_{cr} and V_u approaches the plastic shear strength V_p. The LFS web plate no longer buckles and is observed to reach full von Mises yield at its ultimate state. The f_n=2 design has a significant (76%) increase in V_u compared to the flat web specimen (f_n=0). The LFS web girders practically reach V_p (within 1%) for all specimens at f_n=2.5 and above, implying that any higher frequency would practically achieve this plastic shear strength V_p result at this imperfection magnitude. For typical imperfection magnitudes of D/1000 and D/400, LFS wave frequencies of f_n=2.5 or above (i.e. with wavelengths below 1.2 m) allow V_u to approach the web's plastic shear strength V_p (achieving at least 0.85V_p).For the maximum imperfection tolerance of D/100, LFS wave frequency f_n=4 (wavelength equal to 0.74 m) still allows V_u to reach a relatively efficient value of 0.93V_p.

Overall, LFS designs with f_n > 1.5 match or exceed the shear strength of a flat web with a pair of transverse stiffeners at mid-panel (a/D=2 as represented by the dashed line). The only exception is the case for D/100, where the limit would be f_n > 3. These results suggest that examining the cost and durability tradeoffs of LFS webs versus welded stiffeners to achieve a desired shear capacity is warranted.

Although not shown in detail here for brevity, the authors also performed analyses with varying web plate depth and thickness (slenderness) while keeping constant the LFS amplitude = 3 cm, wavelength =1.178 m, and imperfection = D/1000 (Wang et al. 2021). Web depths ranged from 1.27 m to 2.946 m, web slenderness ranged from D/t_w = 133 (1.270 m web) to D/t_w = 309 (2.946 m web), and f_n was kept constant at 2.5. It was found that girders of all depths reach an ultimate shear load V_u greater than 89% of the web's plastic shear strength, except for the highest slenderness (equal to 309). At the highest slenderness, the LFS web girder was still able to achieve 0.74 V_p, close to the recommendation of 0.8 V_p for the efficient design of corrugated webs (Sayed-Ahmed 1998). At a constant slenderness of 133, the ratio of V_u / V_p remains between 0.94 and 0.98; it does not seem to be affected significantly by the depth. The slenderness appears to affect V_u / V_p more than the depth.

4. Material Usage Comparison

Table 2 compares the amount of steel required to fabricate LFS of varying frequencies to a flat web panel. The prototype girder panel has a longitudinal panel length (*a)* equal to 5.892 m [19'-4"] (i.e. four times the depth, *a/D = 4*). The length of web (unfolded length of the sinusoid) is shown for each LFS web frequency and used to calculate the weight of steel. It is seen that the baseline LFS geometry (F2.5-A3) is only 0.6% heavier than the flat web specimen, but it has a significant 63% shear strength increase over the flat web assuming *D*/400 imperfection. It is also seen that the highest LFS frequency (f_n=4) is only ~2% longer than a flat plate, corresponding to a weight increase of less than 2.1 kg/m (1.5 lb/ft) over the typical flat web, but the corresponding strength increase is a significant 87% increase over the flat web. It is noted, however, that in a true beam, an aspect ratio of *a*/D = 4 will be subject to both shear and moment, where the LFS specimens will have a reduced plastic moment capacity compared to the flat plate specimen.

Table 2: Material quantity comparison for different wave frequencies f_n

Specimen name	f_n	**Length of web [a] (m) [ft]**	**Weight of steel[b] (kg/m) [lb/ft]**	**Length Ratio = Weight Ratio [c]**	***Strength*** V_u **[d] (kN)**	***Strength Ratio*** **[c]**	V_u/V_p
Flat web	0	5.892 [19'-4"]	127.2 [85.5]	1.000	1694	1.00	0.52
F1-A3	1	5.898 [19'-4"]	127.3 [85.6]	1.001	1341	0.79	0.42
F2-A3	2	5.916 [19'-5"]	127.7 [85.8]	1.004	2219	1.31	0.69
F2.5-A3 (baseline)	2.5	5.930 [19'-5"]	128.0 [86.0]	1.006	2759	1.63	0.85
F3-A3	3	5.946 [19'-6"]	128.4 [86.3]	1.009	2931	1.73	0.91
F3.5-A3	3.5	5.965 [19'-7"]	128.8 [86.5]	1.012	3069	1.81	0.95
F4-A3	4	5.987 [19'-8"]	129.3 [86.9]	1.016	3163	1.87	0.98

[a] For 5.892 m segment between cross bracing.
[b] Average weight per unit length, based on 5.892 m segment between cross bracing.
[c] Normalized by flat panel, unstiffened ("Flat web").
[d] Determined from FEM with *D*/400 imperfection magnitude assumed.

5. Summary and Conclusions

This paper presented an efficient strategy for increasing the shear capacity of thin steel plates by introducing low-frequency sinusoids (LFS) along the plate's longitudinal axis, with wavelengths on the order of a meter. Experimentally validated nonlinear finite element models enabled a parametric study that examined the effects of the normalized wave frequency (f_n) on the web of deep plate girders, where f_n is defined as the number of half sine waves in a distance 1.473 m (the depth of the prototype web). The effects of frequency were examined while varying the initial imperfection (out-of-flatness) of the LFS web plate. Limit states such as elastic shear buckling load V_{cr}, ultimate shear load V_u, and the plastic shear strength V_p were recorded.

The following summarizes the results of the parametric computational study:

- Substantial increases in shear strength were achieved using LFS webs, improving ultimate shear capacity up to 87% over flat webs.

- Increasing f_n increases V_{cr} significantly. Generally, for f_n values greater than 1.5, an inelastic limit state such as V_u (sometimes nearly equaling V_p) is reached before V_{cr} is achieved.
- The assumed initial geometric imperfection (out-of-flatness) in the LFS web plate has a non-negligible effect on the shear strength of the plate. For example, for f_n = 2.5 and A = 3 cm, V_u for D/400 is 0.86 times that of V_u for D/10,000.
- For sinusoidal wave amplitudes of 3 cm, V_u / V_p ratios of 0.85 or larger are reached if frequencies f_n = 2.5 or greater are employed (given a typical D/400 imperfection), thus indicating that efficiencies equal to or greater than typical corrugated webs can be achieved using LFS.
- Frequencies had a negligible effect on the shear stiffness of the plate for f_n values less than or equal to 2.5. Larger frequency values (shorter than 1.178 m wavelength) decreased the shear stiffness.
- The amount of steel required to fabricate LFS web plates with A = 3cm and f_n ranging from 1 to 4 is less than 1.02 times that of a flat plate.

In conclusion, the parametric computational study indicated that LFS plates lead to increased shear strength with negligible increase in material. Other notable advantages to this LFS strategy include relatively simple fabrication and eliminating welded stiffeners, thus improving fatigue life. These advantages imply an economical advantage as well. It is noted, however, that LFS designs are most efficient in locations with high shear and low moment. Overall, this work concludes that LFS are a viable alternative to traditional shear strength enhancing strategies for thin plates such as corrugations and transverse stiffeners.

Acknowledgments

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