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Effects of Stiffeners on the Warping Resistance of Steel I-Beams

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Abstract* - Building failures, with serious consequences, caused by warping of steel frame I-beams, have occurred in Norway, due to deficient design in areas of negative moment. Investigations by practical experiments, finite element analyses and literature research were conducted to determine whether transverse, longitudinal and box-type stiffener plates will increase warping resistance of an I-beam. Diverging opinions and information on this subject persists. Only IPE-80-beams were used. It was deduced that neither transverse stiffeners nor short longitudinal stiffeners installed at the location of the applied point load at mid-span of a simply supported IPE-80-beam, to any significant degree, for practical structural engineering applications, do increase the warping resistance or load carrying capacity.

***Index Terms*−I-beam, point-load, stiffeners, structural steel design, warping**

I. INTRODUCTION

A. Background of this research effort

In some cases, large sheds have failed due to warping of the main steel I-beam frames. At, and in the vicinity of corners A and B, Fig. 1, a considerable negative moment may occur when the roof is heavily loaded by, for instance, snow. Metal covering on the outside of the frames will normally resist warping in areas away from the corners, but will have no bracing effect on the compression flange, i.e. inner flange, at the corners, Fig. 2. In some cases, transverse stiffeners, Fig. 3, have been installed, Fig. 4. However, warping has occurred in these locations, whether stiffened or not, by transverse stiffeners, with disastrous consequences.

B. Literature investigations

Selberg [1] suggests that one method of stabilizing against warping is to install stiffeners as in Fig. 5. Supposedly, these stiffeners increase the torsional resistance of the beam. However, presumably, only at the very location of the stiffeners. Some engineers do claim that stiffeners, as shown in Fig. 3, installed by welding, will, at least to a certain extent, provide resistance against lateral warping [2]. The reason should be that while the compression flange is in compression, the opposite flange will be in tension, thereby being in a stable condition, and, accordingly, provide a certain stabilizing effect to the compression flange if rigidly connected to it by all around welded stiffeners. The corresponding author of this article, Sørensen, has, during engineering design work in California on offshore drilling rigs, heard this assertion. Selberg [1] also mentions that this may be the case. Larsen [3], on the other hand, firmly maintained that transverse stiffeners do not increase warping resistance.

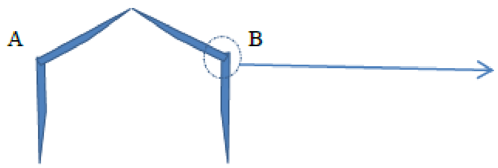

Figure 1. Building frame

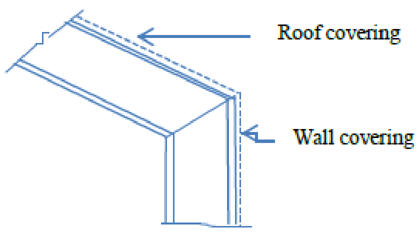

Figure 2. Building frame corner

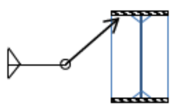

Figure 3. Transverse stiffeners

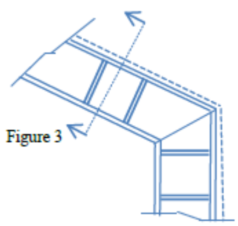

Figure 4. Frame corner with transverse stiffeners

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Fig 5. "Box" stiffeners

Blodgett [4] explains why *transverse stiffeners* have little or no effect on the warping resistance. On the contrary, results of numerical simulations of thin-plate cantilever H-beams by Kreja and Szymczak [5] yielded a 12% increase in warping resistance with stiffeners inserted, as in Fig. 3.

C. What is warping?

When a plate (diaphragm) is being loaded in compression, in its plane, it may suddenly buckle.

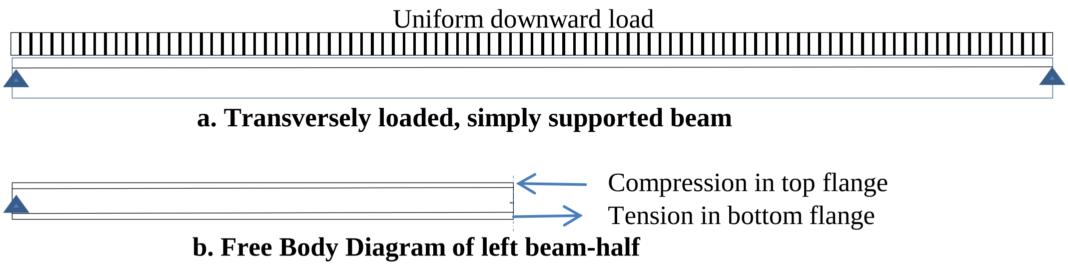
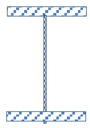


Fig 6. A laterally un-braced I-beam is subject to warping

When a beam is carrying a vertical load, Fig. 6 a, the upper part of the section will be subject to compressive stress in the longitudinal direction of the beam, i.e. the top flange of e.g. a WF-, H- or an I-beam may be regarded as a compression member, Fig. 6 b. Being slender, it will attempt to buckle like a column, when the compressive stress becomes high enough. However, the flange, being connected to the beam-web, cannot buckle. Instead, it twists, or warps, and pulls along with it the beam section into a rotating motion. Lateral support, as being provided by e.g. floor or roof covering, if adequately attached to the top flange, may prevent warping, as will correctly designed and installed lateral struts.

D. IPE-80 section properties

Basic section properties of IPE-80 – beam:
Height: 80 mm
Width : 46 mm
Web thickness: 3.8 mm
Flange thicknesses: 5.2 mm
Cross sectional area: 764 mm^2
Weak axis moment of inertia: 85000 mm^4
Strong axis moment of inertia: 801000 mm^4



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E. Theoretical capacity of an IPE-80 beam without stiffeners

Table I. Computed capacities for supporting a point-load at mid-span of a simply supported IPE-80 beam spanning 5 meters and being fork-supported at the ends, i.e. restrained from rotating about the longitudinal beam axis at the supports.

Point load capacity (N) at midspan computed according to	**Point load applied @ upper flange**	**Point load applied @ bottom flange**	**Lateral compression flange bracing considered**
Pure elastic theory, i.e. no warping considered	5687	5687	Continuous
Norwegian Structural Steel Design Code (NS3472, 2001) [6]	1661	1647	None
Structural Steel Design (Beedle, 1964) [7]	1590	n.a.	None
Stålkonstruksjoner (Larsen, 1997) [8]	1861	2205	None

In Table I, maximum point load values at mid-span of an IPE-80, spanning 5 meters, computed according to a) *pure elastic theory* (disregarding warping), b) unbraced capacity according to *The Norwegian Structural Steel Design Code* [6] and two textbooks: c) [7] and d) [8] are listed.

II. EXPERIMENTS

All tests were performed with IPE-80-beams, yield stress: f_y = 355 MPa. The beam ends were braced against warping, i.e. were prevented from rotating about the longitudinal beam axis, but were free to rotate laterally and vertically.

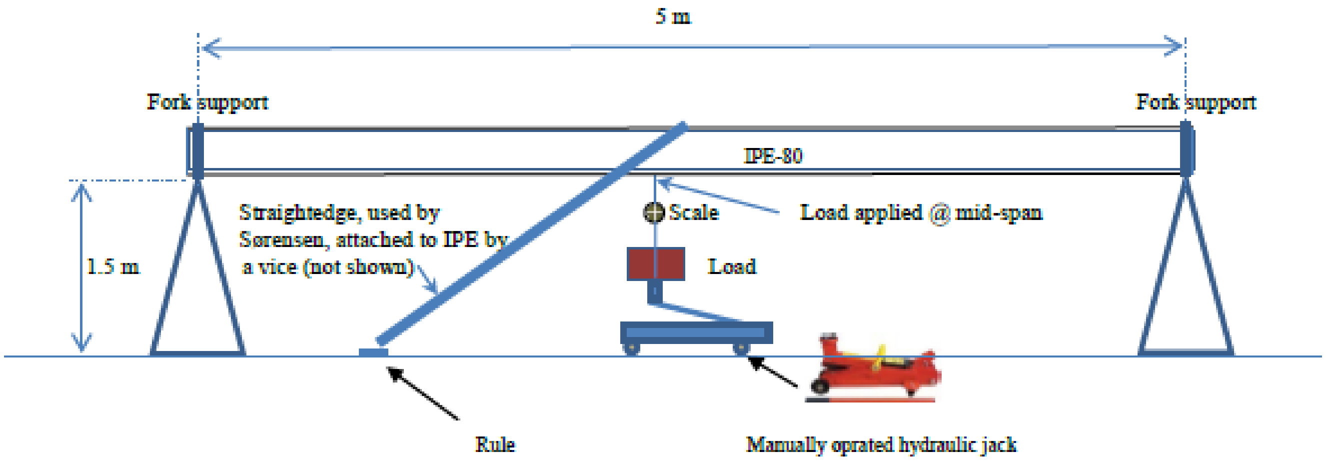

Fig 7. The mechanical test-arrangement

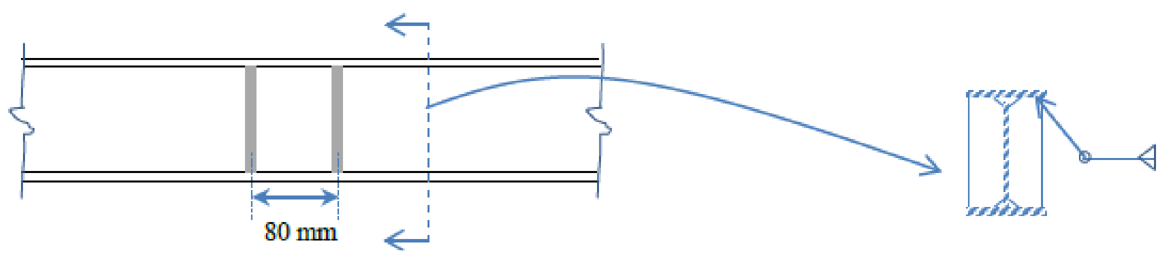

Fig 8. Two transverse 5 mm plate stiffeners each side of the web at the point of load application

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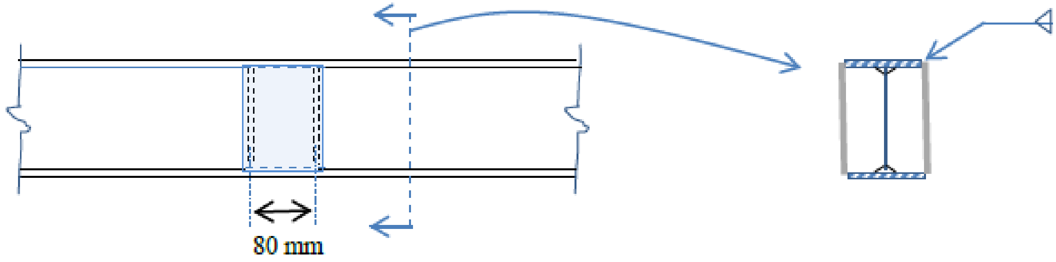

Fig 9. Longitudinal welded-in stiffener plates

A. Mechanical Experiments by Rasmussen

Rasmussen executed tests with alternative load applications to the top and bottom of the beam at mid-span. Electronic measurement devices were installed at mid-span to record distances between the outer parts of flanges, i.e. changes in distances between the outer edges of the tension and compression flanges. Also, the vertical deflection of the beam at midspan was electronically monitored. Three stiffener configurations were utilized:

1. No stiffeners
2. Transverse, welded-in, 5 mm plate Stiffeners, 2 ea. side of web, Fig. 8.
3. Longitudinal 5 mm plate-stiffeners each side of the web, Fig. 9, at the point of load application in addition to transverse stiffeners as in 2. above.

Table II. Results from mechanical tests by Rasmussen

Stiffener configuration, ref. Section IIA	Load applied on top (N)	Load applied at bottom (N)
1 (no stiffeners)	2065[a]	2606[b]
2 (transverse plate stiffeners)	2076[b]	2588[b]
3 (longitudinal and transverse plate stiffeners)	2131[b]	No data

[a]Average of 10 test-runs
[b]Average of 6 test-runs

Each beam was loaded once, then turned upside-down and re-loaded. For several beams, the initial lateral deformation was excessive, and the warping developed gradually, while a considerable vertical deformation took place prior to final failure. To prevent permanent deformation, the vertical deflection was limited to 60 mm max. This way, repetitive tests did not affect the load-carrying capacity significantly. To investigate whether repetitive load applications would reduce the load capacity of a beam, a load causing a 60 mm vertical deflection was repetitively applied 5 times consecutively. The reduction in the load required to cause a 60 mm deflection amounted to 0.6%, which was considered to be insignificant.

No significant change in the shape of sections took place, and the slight change which was recorded, mainly occurred after the initial warping had caused a reduction in the load carrying capacity. The results, listed in Table II, indicate that transverse stiffeners, i.e. configuration 2, at mid-span, do not reduce the tendency of the IPE-80 beams to warp when a point-load is applied at mid-span. The contribution of longitudinal and transverse plate stiffeners, i.e. configuration 3, inserted at mid-span, i.e. at the point of load application, resulted in, for all practical purposes, only a negligible load increase prior to warping. This was likely caused by the local increase in torsional stiffness and increase in moment of inertia at that particular location.

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B. FEM - analyses by Rasmussen

3 types of elements were used for the ANSYS-modeling:

Beam-element	Shell-element	Volume-element
ANSYS BEAM 188	ANSYS SHELL 181	ANSYS SOLID 95

All computations were non-linear, which means that the loads were applied step-wise. Following each load-increment, a new stiffness matrix was developed.
The FEM-modeling was done in ANSYS directly. It was assumed that the beam would deform symmetrically about mid-span. Accordingly, only half the beam-span was modeled, as follows, with axes designations as in Fig. 10:

At mid-span, plane of symmetry:

- Locked against linear displacement in the X – X – direction
- Locked against rotation about the Y – Y – axis
- Locked against rotation about the Z – Z – axis
- Free to rotate about the X – X – axis

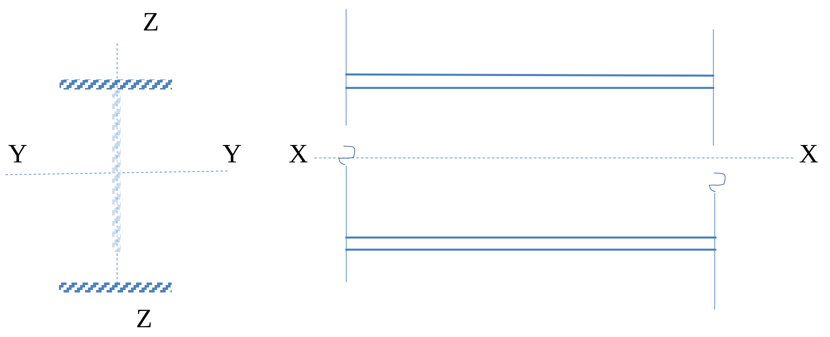

Fig 10. Axes designations

- Free linear displacement in the Z–Z– direction
- Free linear displacement in the Y–Y– direction

At supports:

- Outer parts of flanges locked against linear displacement in Y – Y – direction
- Bottom flange locked against linear displacement in Z – Z – direction
- Section locked against rotation about the X – X – axis
- Section free to rotate about Z – Z – axis
- Section free to rotate about Y – Y – axis

On the outset, FEM-models are perfectly stable, which was not desirable. Two methods of introducing instability were tried out:

1. By letting ANSYS do an eigenvalue-analyses to find the least advantageous warping-mode, for the purpose of updating the geometry based on the warping-analyses executed prior to the application of loads.
2. To apply a tiny load which interrupts the symmetry, thereby causing beam instability.

Both of the above methods yielded nearly equal results. The first method was chosen. The initial lateral deviation ("crookedness") was set to be less than 1.5 mm for all models. The *Arc Length Method* was used for applying loads. For every load-stage, ANSYS finds the equilibrium by utilizing the *Newton-Rapson-method*. Precautions were taken to avoid deviation as the Arc Length Method determines that the next equilibrium will be on a circle-line, which radius corresponds to the arc-length compiled on the basis of the previous load-stage. The results are affected by the size and shape of the elements. Accordingly, results obtained from the FEM-analyses may vary, even if the models are exactly alike, but have a different distribution of elements. All models used for this report were controlled against other models having more

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finely distributed elements. 2.5% variations have been accepted. The term "vertical deflection" in this report means vertical deflection at the point of load application. In this report the term "stiffeners" refers to the type shown in Fig. 3. In Table III, the loads and the corresponding initial deflections at the instant of initial yield stress are listed. Table IV lists the *ultimate* loads, i.e. failure loads, and corresponding deflections. The FEM-analyses indicated that warping would take place prior to yield stress occurring. However, the load increased beyond the load which caused initial yield, until ultimate warping-failure, Table IV. The effects of stiffeners on the load-carrying capacity is, according to the tabulated results, negligible.

Table III. Yield loads on FEM-models and corresponding vertical deflection

	LOAD AT STEEL YIELD (N)		VERTICAL DEFLECTION (mm)	
MODEL TYPE	Load on top	Load at bottom	Load on top	Load at bottom
Shell model w/stiffeners	2032	2500	46.6	47.9
Shell model without stiffeners	2020	2498	46.4	47.4
Volume model with stiffeners	1965	2420	49.5	52.8
Volume model without stiffeners	1962	2418	48.8	52.7

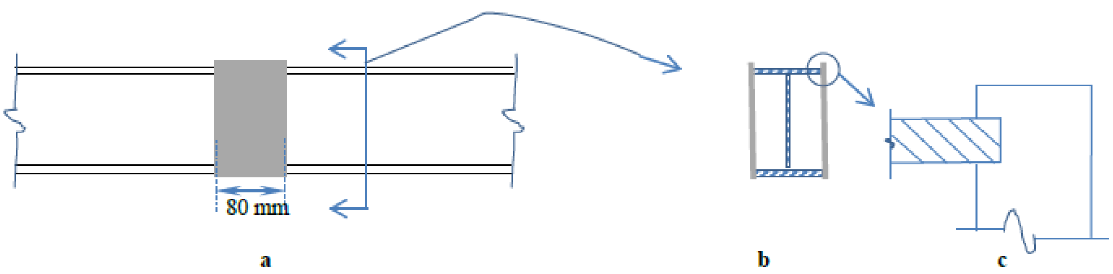
Table IV. Ultimate loads on FEM-models and corresponding vertical deflection

	ULTIMATE LOAD (N)		VERTICAL DEFLECTION (mm)	
MODEL TYPE	Load on top	Load at bottom	Load on top	Load at bottom
Shell model w/stiffeners	2170	2608	82	121
Shell model without stiffeners	2168	2606	81	121
Volume model with stiffeners	2131	2530	86	136
Volume model without stiffeners	2128	2529	84	137

C. Tests conducted by Sørensen

The loads were applied to the bottom flange only, Fig. 7. Initial lateral beam offset ("Crookedness") was measured. For stiffener configuration, refer to Section IIA, except that the longitudinal stiffeners, Type 3, were not welded to the flanges, but installed by mechanical means. Grooves were milled in the plates, Fig. 11, to exactly fit the flanges of the IPE-80, and held in position by vices.

The beam-section rotation at mid-span was monitored by attaching a straightedge to the beam at mid-span, Fig. 7 and Photo 1, and measuring the lateral movement of the lower end of the straightedge as the load gradually increased. The vertical deflection of the beam at mid-span was measured by means of a rule attached vertically to a reference frame, not shown in Fig. 7, but visible in Photo 2. The results, Table V, give no indications of any increased ultimate load capacity, i.e. maximum load prior to warping, due to the longitudinal stiffeners installed by mechanical means, ref. Fig. 11. On the contrary, the transverse stiffeners installed by *welding* resulted in *reduced* load capacity, which may have been caused by residual stresses caused by welding heat.



2 vices, not shown, held plates firmly in position

Fig 11. Longitudinal stiffener arrangement

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Photo 1. Loading arrangement

Photo 2. Warped beam

Table V. Results from the mechanical tests conducted by Sørensen

BEAM DESIGNATION:	A	B	C	D	E
Initial lateral offset[a] (mm)	11	9	5	0	7
NO STIFFENERS					
Load @ warping initiation (N)	2490	2000	1960	1840	1490
Vertical deflection @ warping initiation (mm)	50	60	55	45	45
Mid-section rotation about beam`s longitudinal axis @ warping initiation (degrees)	0.9	7.9	3.9	2.7	3.7
TRANSVERSE STIFFENERS (Ref. to Fig. 3)					
Load @ warping initiation (N)	No Results	1600[b]	No results	1600[b]	1100[c]
Vertical deflection @ warping initiation (mm)	n.a.	45	n.a.	45	45
Mid-section rotation about beam`s longitudinal axis @ warping initiation (degrees)	n.a.	3.7	n.a.	2.9	6.7
LONGITUDINAL AND TRANSVERSE STIFFENERS (Ref. to Fig. 10)					
Load @ warping initiation (N)	2340	1850	1980	1860	1440
Vertical deflection @ warping initiation (mm)	50	55	55	45	35
Mid-section rotation about beam`s longitudinal axis @ warping initiation (degrees)	0.7	4	2.5	2.3	2.8

[a]Horizontal (lateral) out-of-straightness at mid-span
[b]One test-run only
[c]Two test-runs only

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There were slight indications of the longitudinal stiffeners reducing the transverse rotation of the beam section at mid-span. This, however, is of no "real-life" significance, as the maximum load capacity remains unaltered, and, anyway, is reached prior to the initial warping taking place. The rotation of the beam`s mid-section generally increased with higher initial lateral deflections for beams B, C, D and E, beam A being an exception.

III. CONCLUSIONS

On the basis of the literature studies, practical tests and Finite Elements Analyses performed, the conclusion drawn is that neither transverse stiffeners nor transverse stiffeners in combination with short longitudinal stiffeners installed at the location of the applied point load at mid-span of an IPE-80 beam, to any significant degree, for practical engineering applications, do increase the warping resistance or load-carrying capacity.

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REFERENCES

[1] Selberg, Arne, Stålkonstruksjoner (Steel Structures), ISBN 8251900050, Tapir Forlag, Trondheim, Norway, 1971. 490-491.

[2] AISC Engineering Tips Forum, www.eng-tips.com, December 9, 2005.

[3] Larsen, Per Kristian, quote, Professor of Structural Steel Design, The Norwegian Technical University, Trondheim, 2006.

[4] Blodgett, Omer W., Article: «No Twisters or Swingers Allowed», Welding Magazine, May 1, 2008.

[5] Kreja, I. and Szymczak, C., Numerical Simulation of a Thin-Walled Beam with Warping Stiffeners undergoing Torsion, Civil Engineering Faculty, Gdansk University of Technology, Gdansk, Poland, 2002.

[6] NS3472, 3rd Edition, Norges Standardiseringsforbund – Norsk Standard, (Steel Structures, Design Guidelines – Norwegian Code), Oslo, Norway, 2001.

[7] Beedle, L. S. *et al.*, Structural Steel Design, Lehigh University, The Ronald Press Company, New York, 1964. 196-204.

[8] Larsen, Per Kristian, Dimensjonering av Stålkonstruksjoner (Structural Steel Design), ISBN 8251909465, Tapir Forlag, Trondheim, Norway, 1997. 314-320.

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