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Ultimate Strength of Frames and Grillages Subject to Lateral Loads – an Experimental Study

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Abstract

This paper describes experimental research conducted in part for the Ship Structures Committee project # 1442 - Investigation of Plastic Limit States for Design of Ship Hull Structures. The research program consisted of a series of increasingly large experiments to investigate the plastic behavior of ship framing and grillages subject to lateral loads. The initial tests were conducted as single frames, fixed on the ends and loaded with a small patch load at either the center or near the ends, so that two forms of plastic collapse, bending and shear, could be investigated. After eight single frames were tested, the experiments proceeded to test two small grillages (3 frames attached to one plate panel) and then two large grillages (9 frames plus two stringers, attached to 3 plate panels, in a 6.8m x 2.46m panel). The experimental procedures, data sensors and the full range of results are described. Extensive ANSYS finite element analysis of frames has been conducted, and some comparisons are presented. The study found a number of interesting relationships between various buckling mechanisms (shear buckling, web compression buckling and tripping) and the overall plastic collapse. Implications for design, especially goal-based design, are discussed.

Keywords

Ship structures; Plastic limit states; Experiments; Finite element analysis; Nonlinear; Ship design.

Introduction

The design of ship structures is undergoing considerable change. The reasons for the change are many. New and larger ships are continuing to address new commercial opportunities. Continuing improvements in materials and ship construction technology are encouraging change. The constant improvement of computational power is letting researchers and designers contemplate and execute ever more sophisticated simulations of ship structural behavior (loads and failure mechanisms). An increasingly sensitive public has lead to demands on the governments, shipping companies and classification societies to find way to make ships safer. The International Maritime Organization (IMO) is the focal point for much of the discussion and debate.

As part of this trend, new ship structural rules are going beyond the traditional approach of just checking structures against a yielding criterion. The ice class rules developed during the 1980s and 90s (Transport Canada 1995, IACS 2006) have all been formulated using plastic limit states for the sizing of plating and framing. The new IACS Common Structural Rules (IACS 2005) have included certain assessment of plastic limit states in their formulations.

The research described here is being conducted as part of a comprehensive study of the ultimate strength of ships frames (Daley, Pavic and Hermanski, 2004; Daley and Hermanski, 2005). The current focus is on frames subject to intense local lateral loads, such as ice loads. The work was begun with support from Transport Canada to study single frames. Eight single frames were tested. The US Coast Guard then joined in the project and enabled an expansion of the experimental and numerical analysis to include the testing of two three-frame grillages. The experimental program was then further expanded with the support of the Ship Structures Committee, which funded the experimental investigation of two large grillages.

This paper represents a summary and overview of the work. The complete set of results will be reported to the Ship Structures committee in a comprehensive report.

Experimental Program

The experimental program has provided empirical evidence to support the numerical and analytical investigations. The experiments explored the influence of frame geometry (for single frames), load position (central and end) and frame boundary conditions. In ships, any single frame is joined laterally to neighboring frames through the shell plating. At their ends, frames typically continue to the next bay, through a supporting stringer (or similar). The experiments examined a range of frame support conditions. In the single frame tests, the frame ends are held rigidly (as rigidly as possible), while the sides were free. In the small grillage the ends were held rigidly, while to the side (of the central frame) there was plating and a similar frame. Also attached to the plate beside the side frames, there is a heavy bar that is designed to approximate additional frames. This construction created realistic boundary conditions to the side of the test frame. In the large grillage the frames continued through a stringer and on to a remote fixed support. Thus in the large grillage, both the side and end conditions (for the central frame) are realistic. Fig. 1 shows the cross sections of the frames tested. The grillages were all made with the T75 frame section.

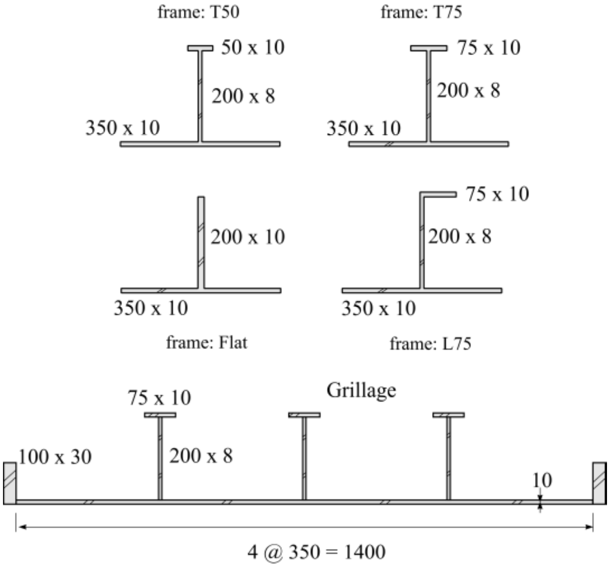


Fig. 1: Frame Sections

Single Frame Tests

The first six single frame tests were conducted using the support frame illustrated in Fig. 2. Photos of two tests are shown in Figures 3 and 4. At first, a 350x350mm (14"x14") silicon filled loading pillow was used to apply the load (see Fig 3). This proved to be problematic, so that after two tests, the load was applied through a 102x102mm (4"x4") square steel block (Fig. 4).

After the first six single frame tests were complete, the new grillage test apparatus was ready for use. This large support structure was then used to test that last two of the single frames (Figures 5 and 6). Table 1 summarizes the eight single frame tests that have been conducted.

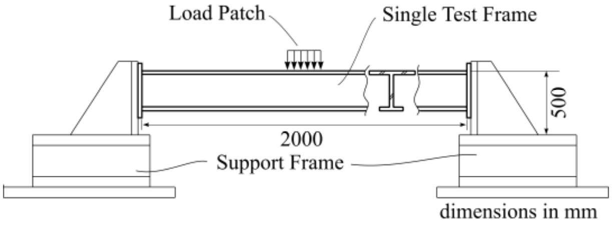


Fig. 2: Single Frame Tests (first six)

Fig. 3: Single Frame Test L75c

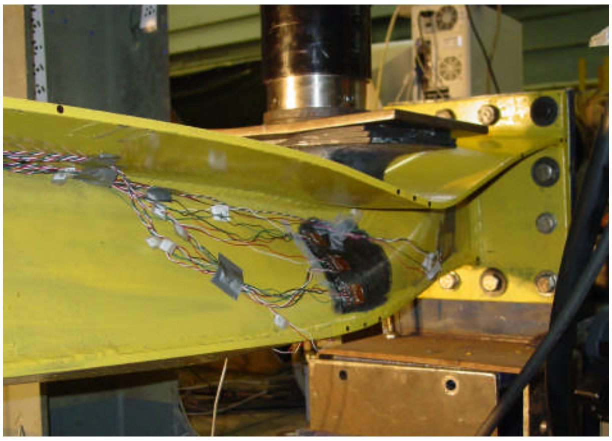


Fig. 4: Single Frame L75e

Table 1: Single Frame Tests Conducted

Test Name	Load Position	Test Date	Frame Description*
L75e	End	8/18/2004	200x8,75x10 L
L75c	Center	10/7/2004	200x8,75x10 L
T75e	End	5/19/2004	200x8,75x10 T
T75c	Center	8/12/2004	200x8,75x10 T
T50e	End	7/16/2004	200x8,50x10 T
T50c	Center	6/16/2005	200x8,50x10 T
Fe	End	7/28/2004	200x10 Fl
Fc	Center	6/6/2005	200x10 Fl

*dimensions in mm.

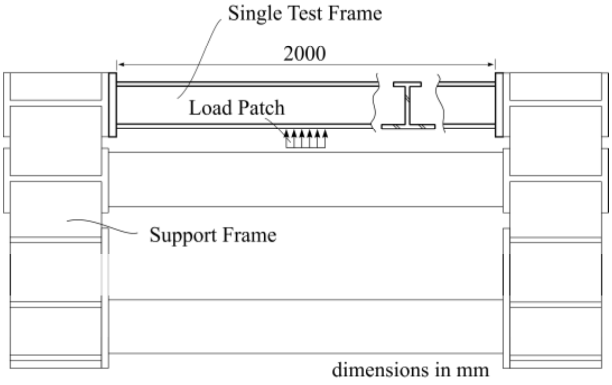


Fig. 5: Single Frame Tests (for T50c and Fc)

Fig. 6: Single Frame Test (Fc)

Data Collection

The components of the data collection system are shown in Fig. 7. The data collection system was very similar for all tests conducted. In the first six single frame tests, the load was measured with a load cell, in line with the actuator. In the later tests, the load was determined by measuring the hydraulic pressure in the load jack. The system was calibrated in a press, to ensure that the calculated and measured loads were in agreement. Strain was measured with a set of resistance strain gauges. The strain gauges were long-elongation gauges, chosen to give values well up into the plastic strain region. Deflections were measured with a set of wire-reel extensometers (‘yo-yo’ pots.). The strain, deflection and loads were all gathered Local deformations were also recorded automatically throughout the test using hardware and software (LabView^{TM}) from National Instruments. In addition, a 3D coordinate measurement device (microscribe from Immersion Corporation) was used to determine the distortion of the frame under load. The microscribe was connected to a computer running Rhinoceros (from McNeel and Associates), where the 3D deformation data was recorded. At each load step, the microscribe was used to manually measure the x,y,z coordinates of about 15 points on the cross section above the load.

In addition to the numerical data, digital still and video images of the tests have been recorded. One 6mp still camera was used to gather time-lapse images of the later tests. These images can be viewed individually or as a motion video. The digital video used DV format tapes.

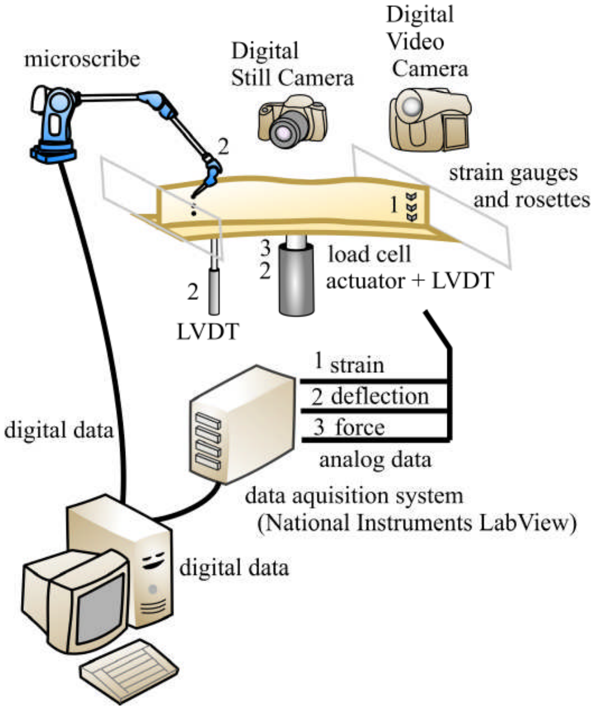


Fig. 7: Data Collection components

Small Grillage Tests

With the single frame tests complete, the next stage was the testing two small grillages. Fig. 8 illustrates the test setup. The ends of the small grillages were bolted into a large support frame. The load was applied from below using a hydraulic jack. One test involved a central load on the central frame, while the other involved an end load on the central frame. Fig. 9 shows the end-loaded small grillage after removal from the test frame. The local distortion of the central frame at the end is clearly visible.

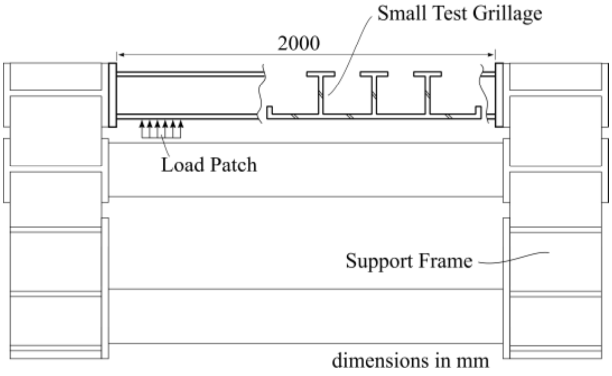


Fig. 8 : Small Grillage Tests

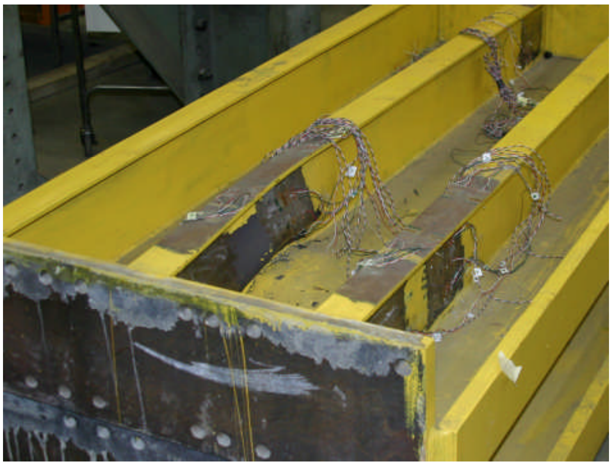


Fig. 9 : Small Grillage Panel after End-Load Test

Large Grillage Tests

The final stage in the current program has been the testing of two large grillages. The grillages are supported in a support frame as illustrated in Fig. 10. Each test grillage is 6.8m (22.8ft) long and 2.46m (7.9ft) wide (Fig. 11). The ends of the 2m frames are supported by a cross stringer with the frames extending through the stringer to a clamped (bolted) support at the extreme ends. The stringers are held by brackets bolted into the main support frame. The load is applied from below as described earlier.

The large grillages were tested with three applications of load, rather than one. After the first load was applied and removed, the hydraulic ram was moved and the structure was tested again. This has given an indication of the capacity of the frames after there is damage at nearby locations. This has proven to be very interesting. It is important to note that all testing should be considered as the testing of one frame. Even in the grillage cases, the load is applied to a single frame. The grillage is there to give the correct boundary conditions for the test frame. It is very interesting to see how much more capacity a frame has when part of a grillage. This increased capacity and increased forces applied, resulted in the large grillages failing finally by punching shear in the 10mm shell plate. The load reached 1470kN, applied through a 102x102mm load patch.

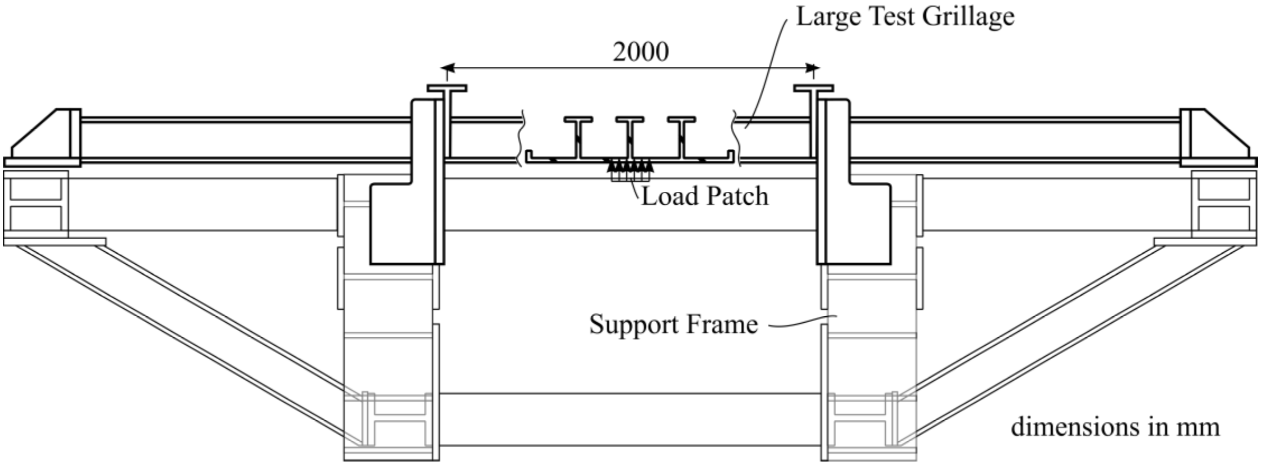


Fig. 10 : Large Grillage Test Setup

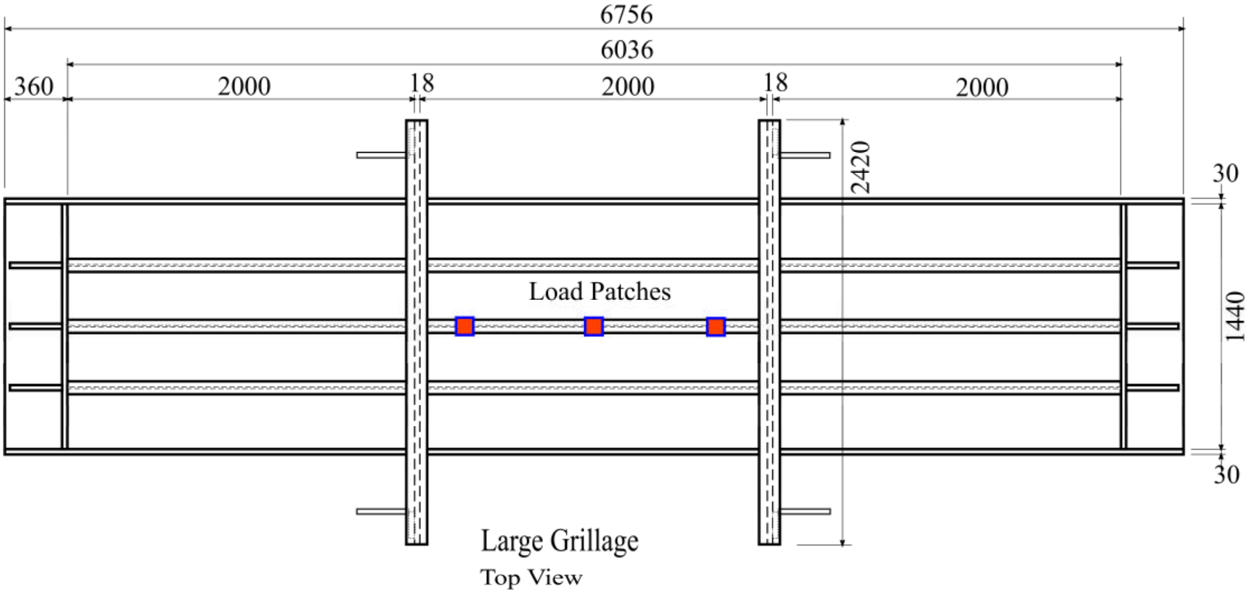


Fig. 11 : Large Grillage Panel Dimensions

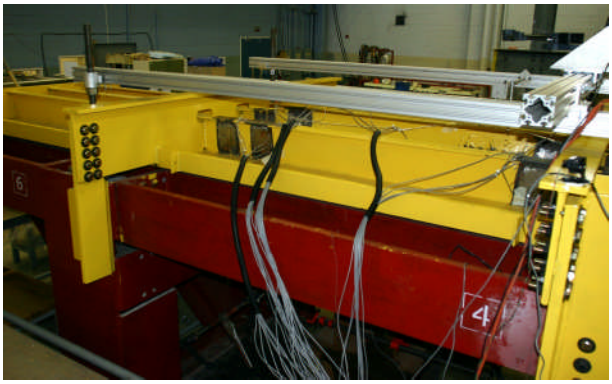


Fig. 12 : Large Grillage Test Arrangement

Samples of Test Results

Fig. 13 shows one of the stress-strain curves taken from a sample of the steel in the webs of the single frames. The steel grade was 300W, a weldable construction steel commonly available in Canada. The measured yield strengths were in the range of 340MPa to 425MPa. Some of the shell plating was made from 250W, and had measured strength as low as 280MPa. Typically the steel exhibited the usual yield plateau, with a subsequent strain hardening region. The (linear-equivalent) post-yield modulus was taking to be about 1.2 GPa.

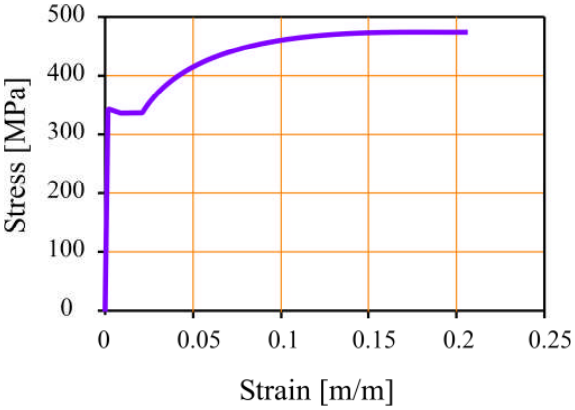


Fig. 13 : Load vs. deflection for three of the single frame tests.

Fig. 14 shows three forces vs. deflection curves for three of the single frame tests. Fig. 15 shows force vs. deflection for one of the large grillage tests. It is clear that the presence of the surrounding frames in a grillage has a significant influence on the capacity of a loaded frame. This would not matter when all frames are loaded similarly and have the same capacity. However, in the case of local loads from ice or small collisions, the surrounding structure plays a significant role in supporting the loaded frame. The initial (linear) region is larger, and the post-yield reserve region is much larger.

Fig. 16 shows how the microscribe data can be viewed after the tests. In this case the measured microscribe point data (x,y,z coordinates) has been used to construct before and after (deformed) sections of the test frame. This data can be subsequently used to compare with finite element simulations of the tests.

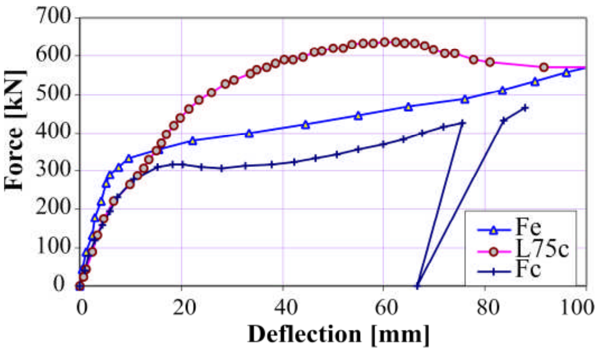


Fig. 14 : Load vs. deflection for three of the single frame tests.

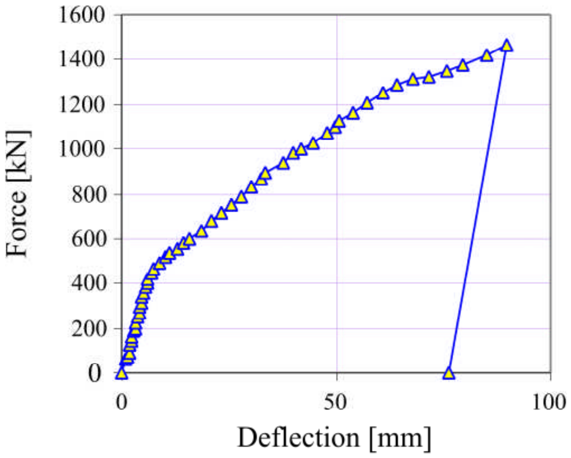


Fig. 15 : Load vs. deflection for the 2nd Large Grillage Test (end load)

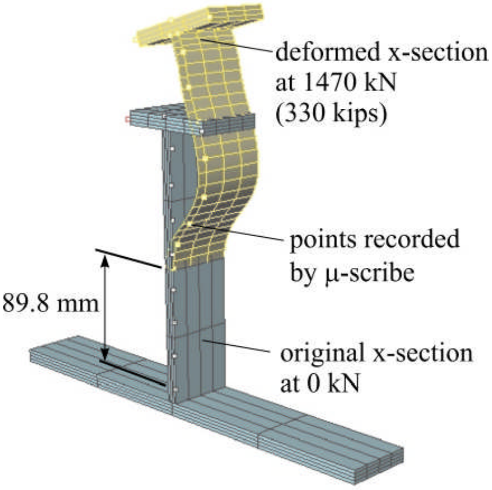


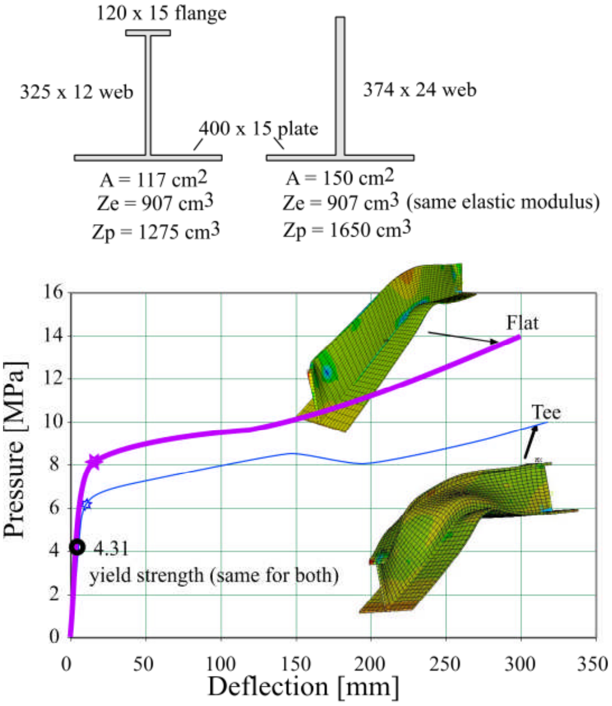
Fig. 16 : Microscribe data for first and last load step on Large Grillage Test LG2

Fig. 17 shows one of the many photos taken during the tests. This one illustrates the web buckling which occurred during the large grillage end-load test. The photo also shows one of the intriguing plastic phenomena which was seen in various forms in many tests. The paint is showing a pattern of failure which is believed to reflect plastic shear slip planes in the underlying steel. While not initially intended as such, the paint acted as a strain visualization coating. While this only occurred at very large deformations (well above yield), it showed that the steel tended to form ‘fingers’ when highly stressed in shear. This may be peculiar to the particular steel used in the tests, or this may be a more general result. This kind of strain localization is very difficult to create in a finite element model, and would normally not be seen in finite element models. These ‘fingers’ imply very high local strains, and may well have a significance for later fatigue strength. Note that there are both horizontal and vertical finger patterns showing in Fig.17. Such fingers would also tend to cause coating breakdown, and so would have an impact on the corrosion process. The fingers did not appear to affect the overall frame capacity.

Fig. 17: Web of Large Grillage test LG2.

Discussion

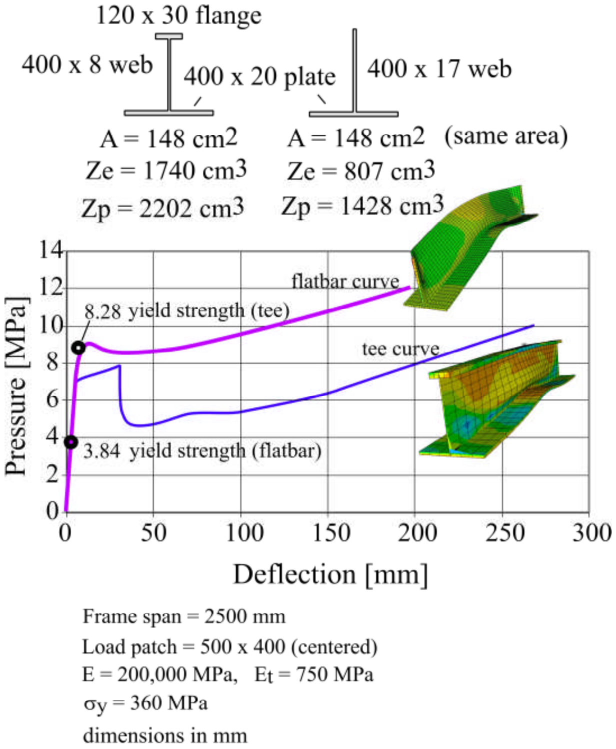
The experiments described above provide insight into the plastic behavior and reserve capacity of ship frames. Fig. 15, for example, shows that there is a very large plastic capacity reserve, and that even with loads of say twice yield, the frame deflections would remain less than 1% of the frame span. Ship structural design can benefit greatly if this kind of behavior is considered at the design stage. Traditionally, ship structures have been designed using ‘working stress’ methods. This approach considers the elastic stresses in a structure and sets limits on stresses. Consequently, the elastic properties of structures (e.g. moment of inertia, elastic section modulus) are controlled and optimized. Unfortunately, this approach does not assure that structures behave adequately in overload situations. Consider the two frames sketched in Fig. 18. The two frames have the same elastic section modulus, though all other geometric measures (area, inertia) are different. The two frames would be considered equally satisfactory in any ‘working stress’ design. However, they have quite different plastic capacities. Fig. 18 illustrates the different plastic behaviors of the two frames. The flat bar frames has greater initial capacity, followed by a greater reserve and more stable behavior. The flat bar stays upright while the tee section folds over under high loads. Not all flatbar frames will outperform flanged frames. The comparisons will be quite dependent on the specific geometry.



Frame span = 3000 mm
Load patch = 500 x 400 (centered)
$E = 200{,}000$ MPa, $E_t = 500$ MPa
$\sigma_y = 360$ MPa
dimensions in mm

Fig. 18 Comparison of load-deflection behavior of two equal modulus frames.

The frames in Fig. 18 have identical modulus, but not the same weight. From one perspective the figure shows the value of considering plastic capacity, but at the cost of steel weight. In this way, conventional rules result in the flatbar being doubly penalized, once by not recognizing its superior linear and reserve performance, and secondly by adding steel weight. The next comparison shows an example where the frame weights are identical. Fig. 19 shows two frames with the same weight. The tee section has a very thin web, at the limit of allowable thickness (for buckling). The flatbar actually exceeds the usual aspect ratio, but still behaves acceptably. Fig. 19 compares the load-deflection curves for the two frames. Also shown are the nominal yield capacities (load which would case yield stress in simple bending). Note that the flatbar has a lower elastic modulus, but is both initially and ultimately stronger than the slender tee. This demonstrates a number of important points. The first is that elastic properties may have little relation to structural behavior. Second is that even the plastic section modulus may be a poor indicator of capacity, especially if plastic bending is not the dominant plastic structural mechanism. The design rules should reflect actual capacity, rather than using a single simple measure like modulus.



Frame span = 2500 mm
Load patch = 500 x 400 (centered)
E = 200,000 MPa, Et = 750 MPa
σ_y = 360 MPa
dimensions in mm

Fig. 19 Comparison of load-deflection behavior of two equal weight frames.

Fig 20 sketches the typical load deflection pattern that we tend to have in laterally loaded frames. The deflection is the maximum deflection of the web under at the plate-web connection. After yield, but prior to the full formation of mechanism 1, the load-deflection curve is essentially linear and follows the slope of the original elastic trend. Yielding occurs well before mechanism 1, and initially produces a tiny volume of yielded material. This is followed by the expansion of the yield zone, during which stress redistribution takes place. Once the plastic zone fills one or more critical cross sections, a plastic mechanism forms that allows large and permanent deformations to occur. Mechanism 1 might be called 'collapse', though this term is not exactly correct. Subsequent to mechanism 1, while the frame is 'collapsing' in bending, internal forces tend to rise and support the growing load. Further along this curve, additional mechanisms can occur, including buckling and fracture. There is no standard way to evaluate frames that takes into account this multiplicity of behaviors.

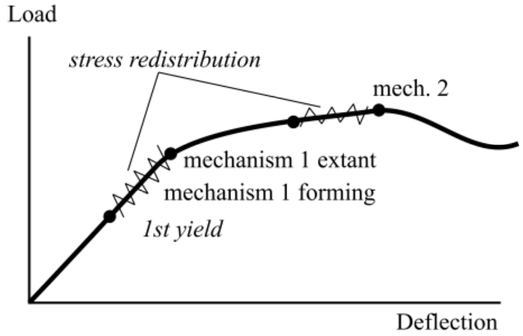


Fig 20. Idealized load-deflection curve for a frame.

Conclusions

The results and descriptions presented have been an overview of a large series of structural experiments conducted at Memorial University. The results will be fully described in a Ship Structures Committee (SSC) report. The experiments have shown a number of interesting and in some cases surprising results. It is clear that a simple measure such as elastic section modulus is not representative of the capacity of a ship frame, especially as regards the full behavior and post-yield reserve. It may well not even be a good indicator of the linear range capacity. Another surprising result is the post-damage capacity of frames. Small damages appear to strengthen, not weaken, the surrounding structure. This has implications for inspection and timing of repairs. And finally, the presence of shear strain localization (fingering) deserves further attention, especially as it may affect fatigue and corrosion of dented structures.

Acknowledgement

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