Experimental evaluation of stiffened curved plates subjected to pure compression

Sara Piculin¹, Franc Sinur¹, Primož Može¹

¹University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova 2, 1000 Ljubljana, Slovenia

E-mail: sara.piculin@fgg.uni-lj.si

Abstract. The paper deals with an extensive experimental study on five stiffened curved plates with different geometry and steel grade. The objective of the study is to analyse the behaviour of curved panels and their longitudinal and transverse stiffeners subjected to pure compression. Before testing, the initial geometric imperfections of the specimens were measured. They will be further used in the finite element model as initial geometry. During tests, the displacement field was measured with photogrammetry. In this paper, some results of the experimental tests are presented together with a study of the effects of different parameters on the element’s resistance to pure compression. It is shown that the displacements provided by photogrammetry are in good agreement with those measured with LVDTs in discrete points. The ultimate force of the specimen made of higher steel grade does not differ significantly from other specimens. In addition, there is almost no difference in the resistance between plates with different aspect ratios. Initial imperfections and residual stresses play an important role in the prediction of the stiffened curved plate’s response when subjected to pure compression.

1. Introduction
The use of curved steel panels in bridge design of steel and steel-concrete composite decks has been increasing in the past few years due to both aesthetical and structural demands. Curved panels can represent the web of horizontally curved girder or, as discussed in the present study, transversally curved plates represent the lower flange of a box-girder. The curved lower flange is longitudinally welded to vertical or inclined web plates in order to form a closed box-section. In some cases, the curved flange can also play the role of both the web and the flange (see Figure 1). Usually, the flanges are designed to be slender and are therefore longitudinally stiffened with open or closed stiffeners that increase their load-carrying capacity and, at the same time, lower the weight of the construction.

In the past years, structural engineers are increasingly using this type of elements in bridge design. This was showed recently by Reis et al. [1] that identified in their survey almost 20 roadway, railway and pedestrian bridges in Europe, where curved bottom flange plates were adopted. The structural systems of those bridges are diverse, but mostly cable-stayed.

Although many applications including transversally curved plates are possible, the design recommendations and the knowledge in this field remain scarce. The design of curved panel segments is not covered by the Structural Eurocodes. In fact, the two codes covering shell elements, namely EN 1993-1-5 [2] and EN 1993-1-6 [3], are limited to flat or slightly curved (curvature parameter Z < 1.0) shell elements and shells of revolution. It has been proven by several authors, that curved panels have
different characteristics from both mentioned types of shells [4, 5] and a sophisticated FEM analysis is necessary in order to properly calculate the ultimate resistance of these elements. For this reason, several authors have proposed different methods for the calculation of elastic buckling stress and ultimate resistance of curved panels [6].

Figure 1. Cross-section shapes including curved plates.

None of the beforehand mentioned methods has any experimental background. In general, experimental tests in this field are very rare. Quite some experimental work was done on flat slander plates with stiffeners [7], but the same cannot be stated for curved panels. Ljubinkovic et al. [8] recently performed an experimental analysis of cylindrically curved unstiffened panels. One of the main conclusions was that special attention has to be given to the modelling of initial imperfections in order to achieve good correlation between experimental and numerical results. There were some experiments on stiffened curved panels carried out in the 30’s (see [9]), but in all cases, the specimen’s material is aluminum alloy. In a recent study, Cho et al. [10] conducted axial compression tests on six curved stiffened plates. The specimen geometry was defined based on a ship survey, also the material and shape of stiffeners are not directly applicable to bridge design. Therefore, the need of an experimental evaluation of stiffened curved bridge segments is obvious.

Since bottom flanges of box girders are subjected to high compressive forces, namely at pier sections, a series of five experimental tests on stiffened curved steel panels under in-plane compression are presented in this paper. The purpose of these experimental tests was to investigate the fundamental characteristics of the buckling and post-buckling behavior of stiffened curved panels and identify their ultimate resistance. Results of the experimental study will represent the database for the calibration of FE numerical models.

2. Experimental tests
Axial compression tests were conducted on five specimens in order to provide experimental information on the structural behavior of stiffened curved plates.

2.1. Specimen geometry and material properties
To analyze the effect of slenderness, aspect ratio and material grade on the plate’s resistance, the five specimens under consideration differ in either geometry or material. Geometric parameters that are equal for all specimens are listed in the left part of Table 1, other geometric and material properties are also given in the table. Notations for the main parameters that are used to describe the geometry of a stiffened curved plate are provided in Figure 2. Additionally, the curvature of a cylindrically curved panel is denoted with the global curvature parameter $Z$. In case of stiffened plates, the local curvature parameter for unstiffened sub-panels is defined by the following expression:

$$Z_{loc} = b_{loc}^2/(R \cdot t)$$

(1)

The local aspect ratio is the ratio between the subpanel’s length and width:

$$\alpha_{loc} = a/b_{loc}$$

(2)

All specimens have two flat longitudinal stiffeners and all have three transverse stiffeners, except for 5C that has only one. Four specimens are made of steel grade S460 and one of grade S690. Mechanical properties of the used materials were provided with standardized tensile tests.
Figure 2. Geometry of test specimen

Table 1. Geometric and material parameters

| Specimen | L [mm] | R [mm] | b [mm] | $b_{loc}$ [mm] | $h_{ld}$ [mm] | $t_{ld}$ [mm] | $Z_{loc}$ [mm] | $h_{st}/t_{st}$ [mm] | Material |
|----------|--------|--------|--------|---------------|--------------|-------------|--------------|-----------------|----------|
| 1C       | 6      | 432    | 2.3    | 12            | 50/5         | S460        |
| 2C       | 6      | 432    | 2.3    | 12            | 50/4         | S460        |
| 3C       | 1728   | 500    | 570    | 190           | 90/4         | S460        |
| 4C       | 4      | 432    | 2.3    | 18            | 50/4         | S690        |
| 5C       | 4      | 864    | 4.6    | 18            | 50/6         | S460        |

2.2. Test layout

Experimental tests were carried out at the Laboratory of Structural and Traffic Engineering, Faculty of Civil and Geodetic Engineering, University of Ljubljana. Tests were displacement controlled with monotonously increased displacement up to collapse.

The main challenge during the design of the test layout was to imitate the desired loading and boundary conditions. Since the panels under investigation are subjected to pure compression, the configuration of the test frame had to be carefully designed in order to avoid any eccentricity during load application. For this purpose, each specimen was welded on the top and bottom edge to a 30 mm thick steel plate that served as a connection to the test frame. The center of gravity of each specimen’s cross-section was positioned in the center of the plate. The top plate was further bolted on a stiff beam on which the load was applied with a hydraulic piston with maximum capacity of 3000 kN that was installed on the main testing frame. The beam was supported in the out of plane direction through a Teflon plate that allows vertical displacements. The bottom plate was also connected to a stiff beam that transferred the reaction forces to the floor through a concrete brick. Both beams were supported out-of-plane to the reaction wall. Vertical edges of the specimen were simply supported. For that purpose, special linear supports were designed in order to prevent the out of plane displacement of the vertical edge, allow the rotation around the vertical axis and the vertical and circumferential displacement. The linear supports were connected to two vertical columns that were supported laterally and out of plane. The test layout is presented in Figure 3 and Figure 4.
2.3. Instrumentation and measuring

With the scope of making an accurate evaluation of the response of the curved plates, several instrumentation was used in order to measure various parameters before, during and after the test. The measured quantities will be used in the calibration of the finite element model.

Before the test, a structured light portable 3D scanner was used to measure the exact initial geometric imperfections of the specimens. The output of the measurement is a very precise CAD model of the scanned specimens that can be compared to the “ideal” geometry of the specimens. This allows the definition of an exact initial geometry that will be further used in the finite element model.

The displacement field of the tested panel at different loading levels was measured by using photogrammetry. For this purpose, the panel was painted in random speckle pattern. In addition, approximately 40 coded targets were attached to the panel to track the displacements in discrete points at each step of the loading. Load application was paused according to a predefined loading protocol and during each pause 12 photos were taken from three different angles at four different heights. It is very important to provide appropriate lighting during the procedure to assure high quality of photos.

A total of 19 uni-axial strain gauges (SG) were attached to the specimen to measure the strains in the structure continuously during the loading procedure. 12 SGs were attached to the second subpanel from top and 7 to transverse and longitudinal stiffeners (see Figure 5). The displacements of the specimen and testing frame in some characteristic points were measured by using displacement transducers (LVDT) placed on the laboratory ground in the backside of the specimen. The global vertical displacement of the panel was measured with LVDT V5 that was placed on the loading beam directly beneath the piston. In addition, 2 LVDTs were used to control the vertical displacement of the loading beam, 3 for the out-of-plane displacements and 4 LVDTs to control the displacements of the loading frame (see Figure 6).
3. Experimental results

The ultimate loads reached in the experimental tests are listed in Figure 7 together with diagrams representing the applied load versus the vertical displacement. In addition, the ultimate force of flat plates with the same dimensions was also calculated according to EN 1993-1-5 [2] although the values are not directly comparable since the tested panels are curved. In the calculation, the mechanical properties from tension tests were used. For all specimens, the resistance of curved plates achieved experimentally is 50 to 75% higher compared to the resistance of flat plates calculated according to the effective width method from the codes.

![Figure 6. LVDT position.](image)

![Figure 5. Position of strain gauges on the back and front side.](image)

| Ultimate force [kN] | Experimental | EN1993-1-5 | Difference |
|---------------------|--------------|-------------|------------|
| 1C                  | 2050         | 1252        | 64%        |
| 2C                  | 1938         | 1198        | 62%        |
| 3C                  | 1138         | 708         | 61%        |
| 4C                  | 1353         | 774         | 75%        |
| 5C                  | 1113         | 739         | 51%        |

The vertical displacement was calculated as the difference between the displacement measured in V5 and the displacement of the supporting elements (V3 and V4). It can be observed, that in the case of thicker panels, the difference between the resistance of 1C and 2C is very small, around 6%. Comparing specimens with different steel grades, 4C reached a higher ultimate force compared to 3C. The difference is around 19%, while the difference in the material’s yield strength is around 33%. Also for the aspect ratio, the results show that the parameter does not affect the resistance since the difference between 3C and 5C is almost negligible regardless of the doubled value of aspect ratio in 5C. The difference in the stiffness between 1C and 2C may probably be attributed to different geometric imperfections and residual stresses.
In Figure 8, an example of the comparison between the displacements measured in two discrete points with LVDTs, namely V5 and W1, and values from the photogrammetry procedure is given. Very good correlation between the results is achieved. Therefore, the displacement field can be further used for the calibration of the numerical model and comparison of deformed shapes.

![Figure 8. Comparison of displacements measured with LVDTs and photogrammetry for specimen 3C.](image)

The collapsed shapes of models 2C, 3C, 4C and 5C are shown in Figure 9. According to the observed deformed shapes and measured strains (see Figure 10), failure of all specimens is associated to a combination of buckling and yield of material. Different buckling shapes can be attributed to the effects of initial geometric imperfections and residual stresses. Both mentioned phenomena have to be taken in account when modelling the stiffened curved plate for a finite element analysis.

![Figure 9. Deformed shape at failure for specimens 2C to 5C acquired with photogrammetry.](image)

In Figure 10, the monitored strains from gauges Z1 to Z12 of specimen 3C are plotted. The cross-section is subjected to pure compressive stresses. In the first phase, the measured strains are elastic and almost constant through the whole cross-section. The first half-wave due to buckling happens in the...
left subpanel (front view) which can be seen from the strains (SGs Z7 to Z12), that instantaneously change from compression to tension. Later, the same happens with the other half of the measured strains (SGs Z1 to Z6), when the second half-wave appears.

![Figure 10. Measured strains on the panel for specimen 3C.](image)

The objective of a stiffener is to increase the resistance of the whole plate. Generally, stiffeners may be distinguished between weak that buckle under direct stresses together with the panel and strong stiffeners that provide a rigid support to the panel and enforce the local buckling of the subpanel. According to EN 1993-1-5 [2], when loaded axially, torsional buckling of stiffeners shall be prevented with a sufficient torsional rigidity of the stiffener’s cross-section. Experimental results show that the longitudinal stiffeners in our study provide adequate support to the panel in order to avoid global buckling of the whole plate. It is shown in Figure 9 that local buckling of subpanels predominates in all cases. In all cases, longitudinal stiffeners exhibit torsional buckling.

![Figure 11. Comparison of strains measured in stiffener and panel for specimen 3C.](image)

![Figure 12. Deformed shape of specimen 3C at failure.](image)

In Figure 11, a comparison of measured strains in the right longitudinal stiffener and second panel from top is presented for specimen 3C. Results for 3C are presented because in this case, buckling happened exactly in the panel where strains were measured. It may be seen from the diagram that at first, all three compressive strains are almost equal and are increasing gradually with the increased vertical displacement. The first buckle happens in the left subpanel, the strains change from...
compressive to tensile. Later, the compressive strain in the right longitudinal stiffener increases which is related to the torsional buckling of the stiffener. A few moments later, buckling occurs in the right subpanel. The decrease of the stiffeners stiffness is followed by the buckling of the subpanel and consequently by the decrease in the global resistance of the plate. For a more detailed study on this effect, stiffeners with different cross-sections will be studied in the numerical study.

The torsional buckling of stiffeners may be clearly seen in Figure 12, where the deformed shape of specimen 3C is presented. To avoid the problem of torsional buckling, stiffeners with a closed cross-section are often used and will therefore also be included in the numerical study.

4. Conclusions

In this paper, axial compression tests on five curved stiffened plates are reported. It was found challenging to design an appropriate experimental setup for axial compressive test avoiding eccentricity in the panel. During tests the axial compressive force, strains and displacements were measured. The displacements measured with photogrammetry showed good correlation to those measured with LVDTs. The results provided by photogrammetry will be used for the calibration of a finite element model. Test results show that failure is associated to a combination of buckling and yield of material. The deformed shapes of the specimens are highly affected by imperfections. To demonstrate the effects of imperfections on the plate’s stiffness and resistance, an extensive parametric study will be carried out that will include also different plate curvatures and stiffener geometries.

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