

PEIKKO
**WHITE
PAPER**



DUCTILITY PROJECT
DELTABEAM® SLIM FLOOR SYSTEM

Published 5/2020, updated 10/2022

INTRODUCTION

The global construction market is facing an increasing need to go for solutions that are faster, safer, and more efficient. This means possibilities to build houses with less time and effort on site and lower building life cycle costs without endangering safety. For these needs, Peikko has invented a steel-concrete composite beam known as DELTABEAM® to enable slim floor in multistory buildings.

The benefits of this system are long spans, flexible open spaces, additional room height, easy and space-saving HVAC installations, lower heating and cooling costs, and integrated fireproofing. DELTABEAM® Composite Beam's market position is strong in Northern Europe, mainly in non-seismic areas where hollow-core floors are common. Due to the increased popularity of the shallow floor solution in general and requests by customers, Peikko decided to start a development program to be able to offer a solution for requirements in seismic design. In addition, Eurocodes have requirements concerning robustness and progressive collapse. By combining requirements in these two related design scenarios, Peikko started a program which has been called shortly 'Ductility'. This paper summarizes the first step of the program and presents what has been done and the results.

PEIKKO'S DELTABEAM® COMPOSITE BEAM

In the last decades, there has been an increased interest in slim floor constructions in many countries worldwide. Reduced construction costs combined with the need of new and more efficient ways of designing and building led to this advanced composite system. It was in 1989 when Peikko launched DELTABEAM® to the market, and since then thousands of buildings have been designed and built by using DELTABEAM® Composite Beams.

DELTABEAM® is a steel beam which is integrated into the floor enabling slim-floors. The beam is completely filled with concrete on site and forms a composite structure after the concrete has hardened. Its composite action between steel and concrete allows for open spaces with long spans even for architecturally demanding shapes. Additionally, it can be

used with all common floor types: hollow-core slabs, filigree slabs, composite steel decking, trapezoidal steel decking slabs, and cast-in-situ concrete slabs (figure 1) [1].

DELTABEAM® COMPOSITE BEAM IS PREFERRED OVER OTHER SOLUTIONS THANKS TO THE FOLLOWING BENEFITS:

- Quick and easy installation
- Standardized connections
- Saves construction height
- Easy HVAC installation
- Cost-efficient
- Flexible DELTABEAM® types and details
- Flexible layouts through the whole life cycle
- Fire rating as high as R180 without additional protection
- CE marked
- Enables getting LEED and BREEAM certification points
- Local technical support

AUTHORS:

Simo Peltonen

M.Sc
Senior R&D Manager,
Peikko Group Corporation



Panagiotis Kyriakopoulos

M.Sc
R&D Engineer,
Peikko Group Corporation



There are two types of DELTABEAM®: the D-type and the DR-type. The D-type has ledges on both sides allowing the placement of floor units on both sides of the beam, while the DR-type has a vertical web and ledge only on one side and is mainly used as an edge beam.

DELTABEAMs® can be used as single-span beams or in multi-span beam construction. In multi-span beam construction, Gerber connections, the locations of which are designed by Peikko, provide continuity to the lines of DELTABEAMs®, DELTABEAM® can be combined with all common column types. In cases of concrete columns, the beams are connected to the columns with Peikko's PCs® Corbel [2], a modular hidden column corbel designed especially for DELTABEAM®, or through the columns as shown in figure 2. In cases of steel or composite columns, the beams are mainly fixed to the top of the columns with bolts or welds.

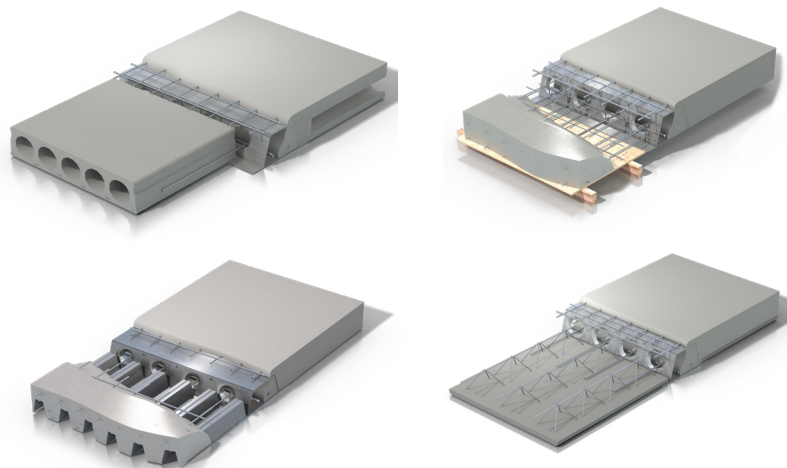


FIGURE 1. COMBINATION OF DELTABEAM® WITH VARIOUS SLAB TYPES

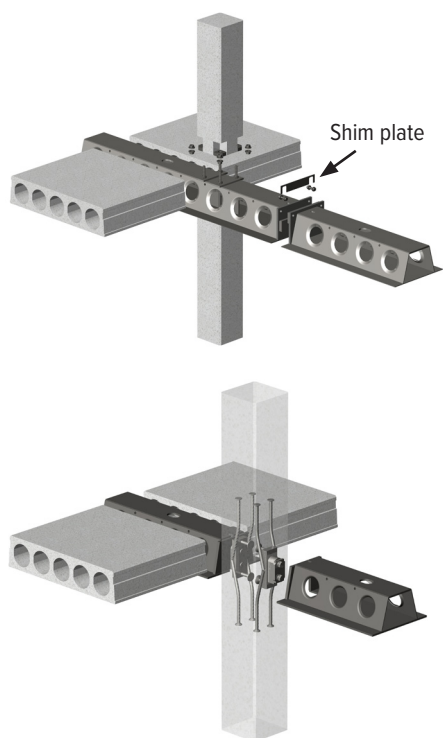


FIGURE 2. CONNECTION OF DELTABEAM® WITH CONCRETE COLUMNS

SCOPE OF THE PROJECT

Devoted to our brand promise of “a faster, safer and more efficient way to design and build”, we do not only supply the market with our products, but we are aiming to lead the constantly evolving construction industry in a manner that fulfills the evolving needs of customers. Lack of any guidance in codes related to shallow (slim) floor constructions combined with a very limited number of tests in technical literature sparked us to start our own experimental project related to DELTABEAM® Composite Beams against extreme situations, like earthquakes or column loss scenarios, in order to provide our customers with a safe, ductile, robust and economical solution.

EXPERIMENTAL INVESTIGATION

Design against extreme load cases demands ductile and flexible structural elements that must have adequate rotational capacity and be able to sustain huge deformations without losing their strength. In order to assess the flexural behavior of DELTABEAM®, 22 full-sized beams with various geometry and reinforcing details have been tested at the Institute of Steel Structures of National Technical University of Athens (NTUA), under both positive (sagging) and negative (hogging) bending loads [3].

The cross-section types of the specimens tested are presented in figure 3. The experimental setup consisted of a steel frame used to support a computer controlled hydraulic




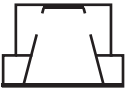



Type 1	 Specimens S2, S3, S4, S5
Type 2	    Specimens S12, H5 Specimens S1, S11 Specimens S15, H6 Specimens S7, H8
Type 3	 Specimens S6a, S6b, S7, S8, H1, H2
Type 4	 Specimens S9, S10, H3, H4

FIGURE 3. CROSS-SECTION DETAILS OF TEST SPECIMENS

actuator and two supports specifically designed for the tests (figure 4). The distance between the central axes of the supports was 7.2 meters. Deflection at middle-span, strains at bottom and top flanges, slips between steel and concrete, and rotations of the specimens were monitored throughout the tests.

The loading protocol was divided in three parts. The first part included three serviceability cycles at displacements approximately equal to $L/260$. The remaining parts included monotonical loading up to the end of the tests with two different speeds.



FIGURE 4. EXPERIMENTAL SETUP

RESULTS

When a structural element or a part of it is subjected to compressive axial loads, some of the plates that contain the element, if they are too slender, may buckle before the element reaches its full strength. This phenomenon, which is called local buckling, is one of the major concerns in the design of steel and composite structures because it essentially defines the strength limit of the elements. Thus, the codes have a classification of steel sections according to their ability to resist local buckling and subsequently their ability to reach their plastic moment and rotational capacity (figure 5):

- **Class 1:** The section can form a plastic hinge and has sufficient rotational capacity to maintain this moment over a considerable range of in-plane rotation
- **Class 2:** The section can develop plastic resistance but has limited rotational capacity to act as a hinge
- **Class 3:** The section can develop elastic resistance of the full cross-section
- **Class 4:** Local buckling of slender elements reduces the elastic resistance; the section can develop elastic resistance of an effective cross-section, smaller than the full section.

This phenomenon does not affect only the plates made of structural steel but also the reinforcement rebars that are under compression leading to unexpected and unwanted cracking of concrete.

Type 1 sections

Type 1 sections were the least reinforced specimens and represent the current configuration of the beams and the reinforcement in the slab. After the maximum load, which was higher than the plastic design resistance of the beam, the concrete under compression at the top of the beam was crushed. As a result of that, the lateral protection provided by the

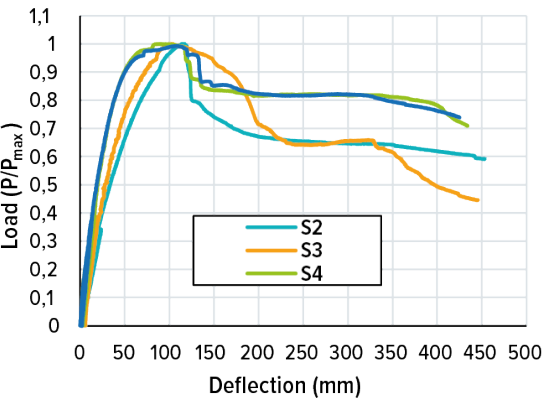


FIGURE 6. TYPE 1 SPECIMENS UNDER POSITIVE BENDING (SAGGING BENDING)

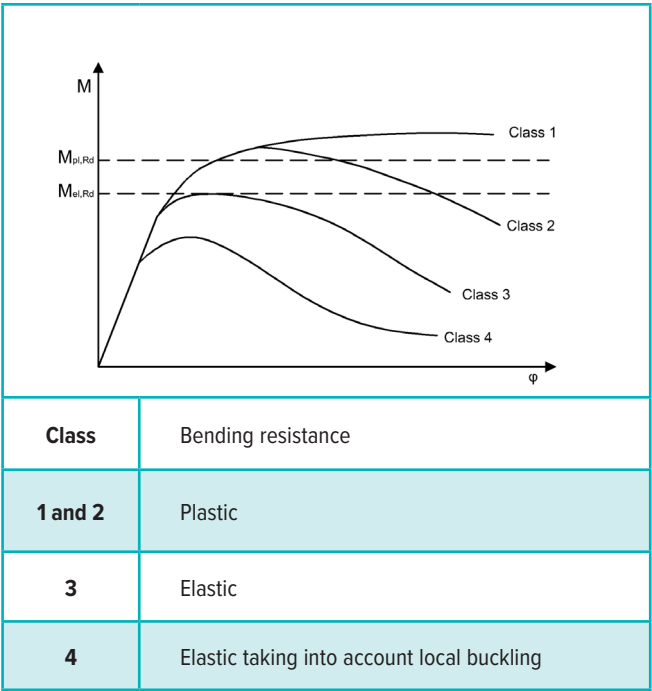
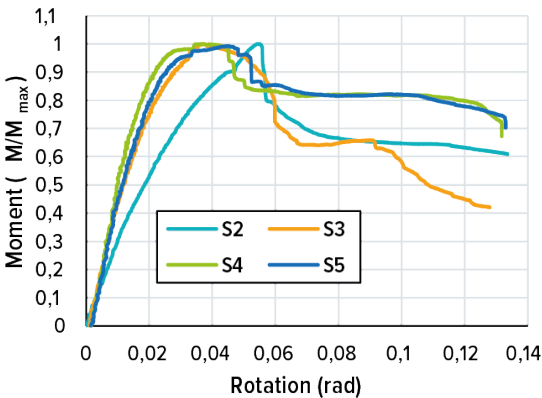


FIGURE 5. DEFINITION OF CLASSES OF COMPOSITE SECTIONS

external concrete to the web and top plates was lost leading to the buckling of these plates (figure 7). This behavior resulted in the reduction of the beams' resistance as can be observed in the load deflection curves (figure 6).



Type 2 sections

The major difference of Type 2 specimens compared to the corresponding ones of Type 1 is the usage of reinforcement in the outer concrete surrounding the DELTABEAM®. All specimens, for both sagging and hogging loads, exhibited hardening behavior after the yielding point on the load- deflection curve (figures 7 and 8). The beams at the end of the tests were in good condition, despite the large permanent deflection,

because the reinforcement and the confinement provided by the stirrups, prevented the spalling of concrete and hence the lateral movement and buckling of the web plates. In cases of specimens with very thin bottom plates under compression (negative bending), the plates, as expected buckled locally. Nevertheless, that didn't affect at all the ductile behavior of these beams and revealed the ability of DELTABEAM® to redistribute the stresses in its steel components without losing its load bearing capacity.

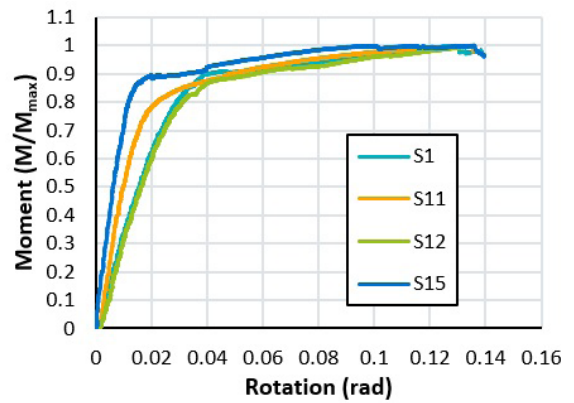
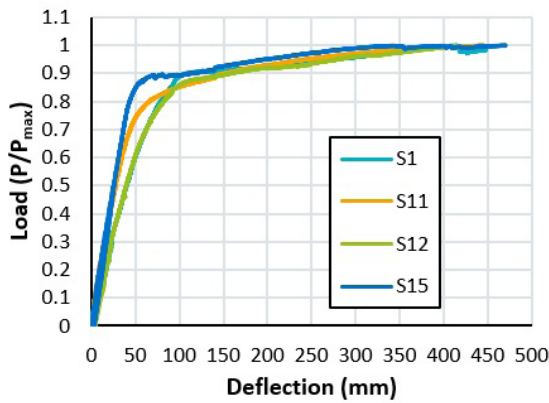


FIGURE 7. TYPE 2 SPECIMENS UNDER POSITIVE BENDING (SAGGING BENDING)

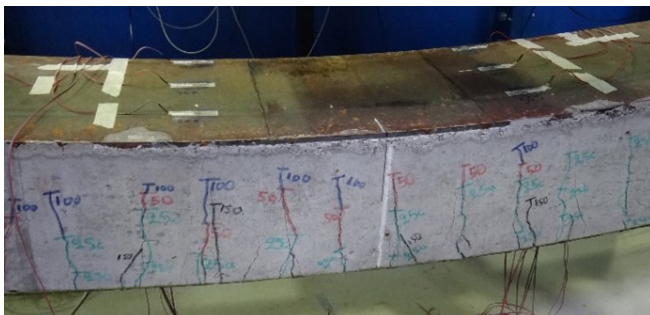
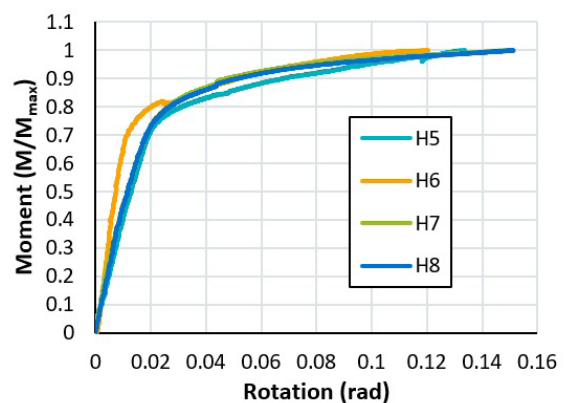
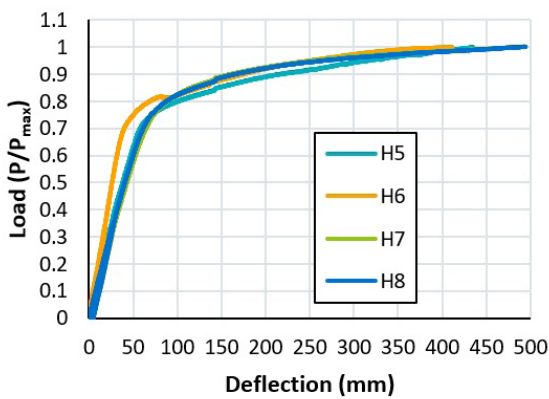


FIGURE 8. TYPE 2 SPECIMENS UNDER NEGATIVE BENDING (HOGGING BENDING)

Type 3

Type 3 beams were the most heavily reinforced specimens. Once more after the onset of yielding all 6 specimens demonstrated a ductile

behavior. The use of steel reinforcement limited the crushing of concrete to a very thin layer, mainly located on the cover above the reinforcement cages.

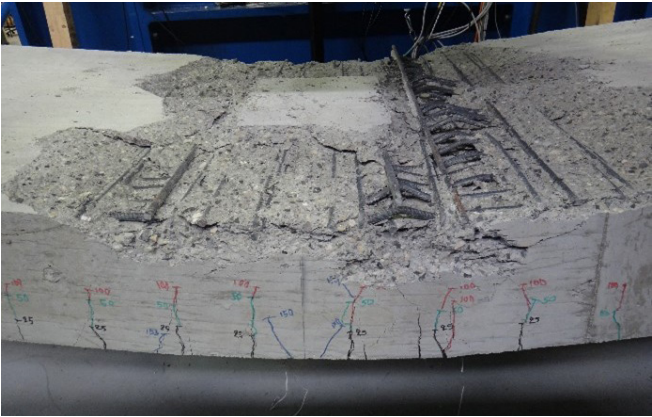
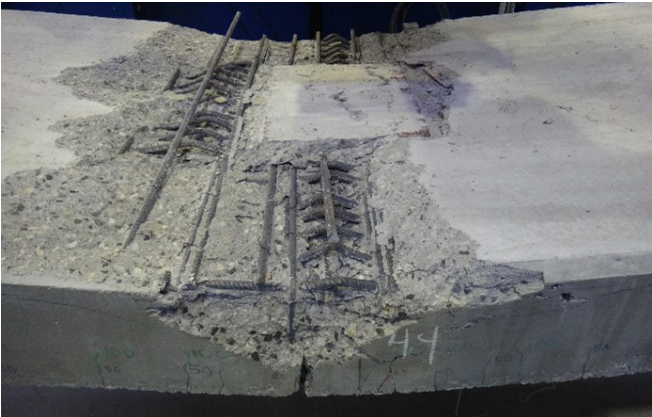
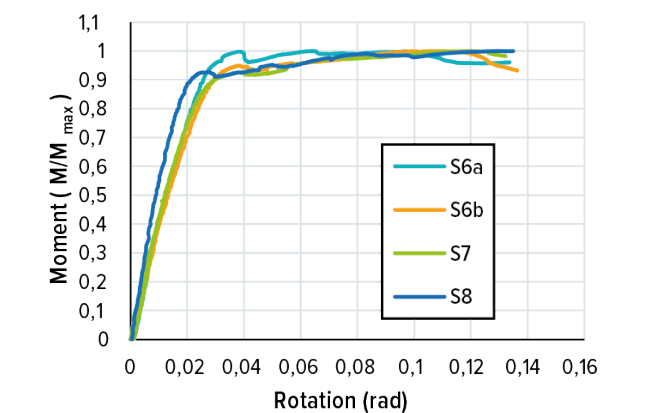
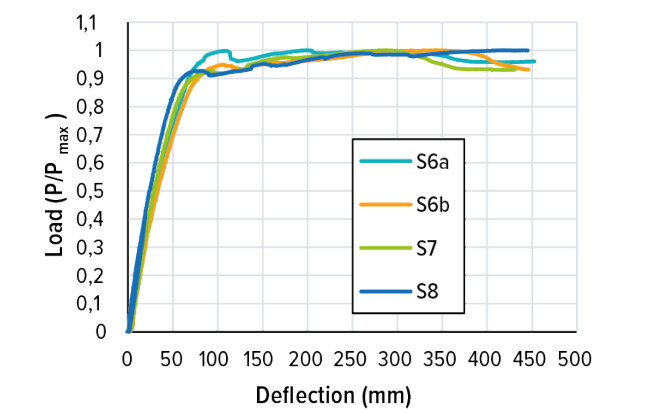


FIGURE 9. TYPE 3 SPECIMENS UNDER POSITIVE BENDING (SAGGING BENDING)

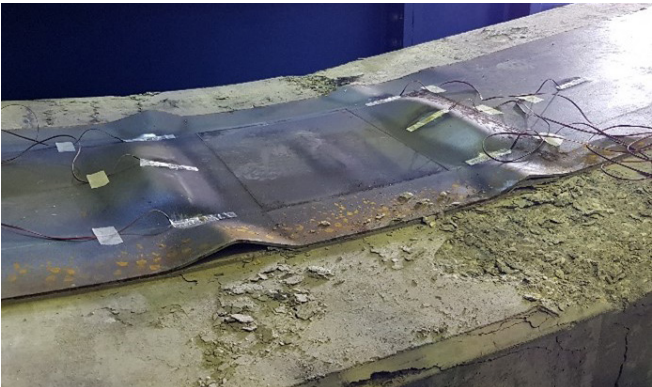
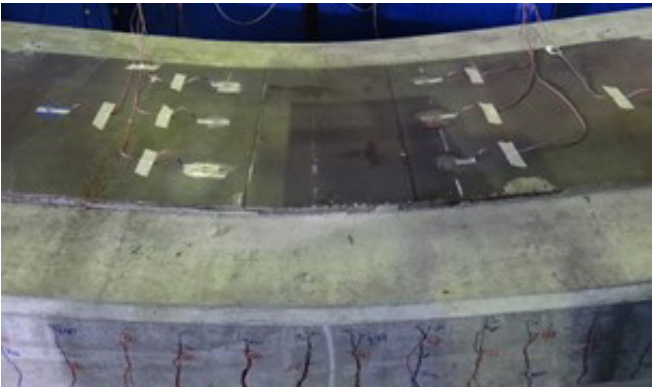
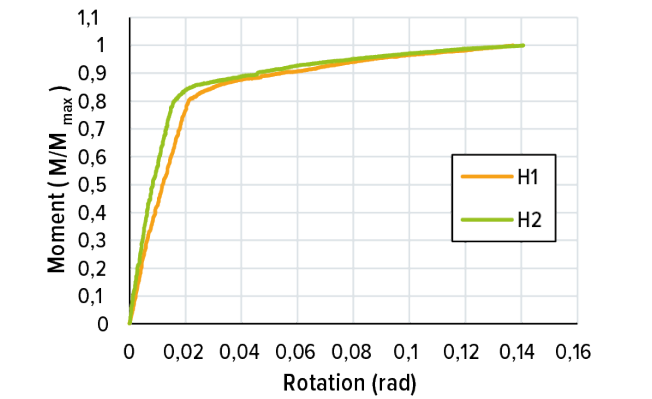
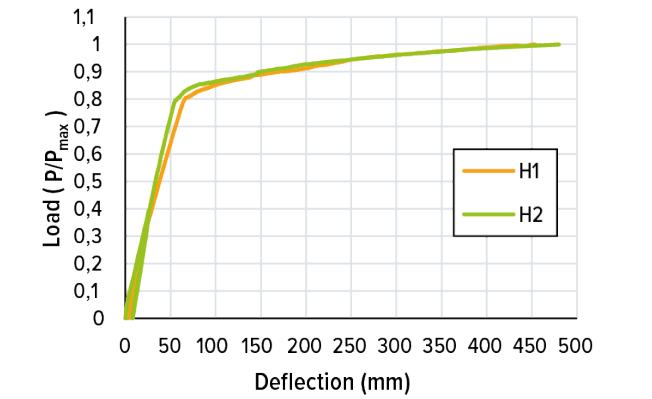


FIGURE 10. TYPE 3 SPECIMENS UNDER NEGATIVE BENDING (HOGGING BENDING)

Type 4 (H3 & H4)

The small strength reductions observed in the curves of Type 4 specimens, given in figure 11, represent the crushing of the concrete ledges at both sides of the beams. However, the main central body of the beams was

protected by the open stirrups and maintained its integrity and its loading bearing capacity. Furthermore, the specimens under negative bending loads also manifested a highly ductile behavior, with the local buckling of the thin bottom plate to not affect the general behavior of the beams.

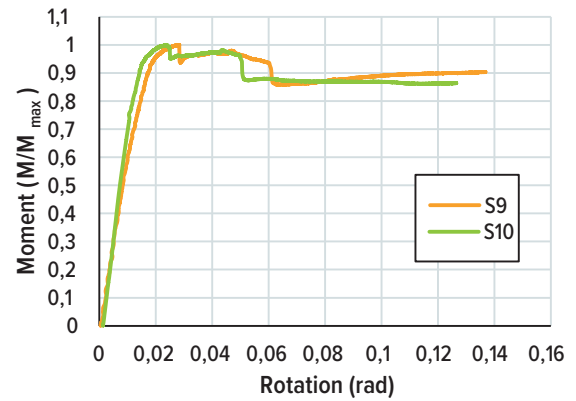
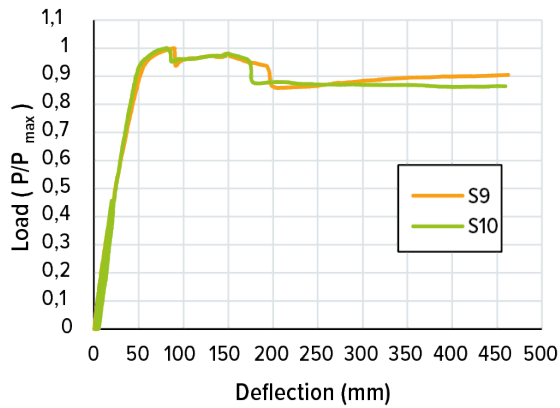


FIGURE 11. TYPE 4 SPECIMENS UNDER POSITIVE BENDING (SAGGING BENDING)

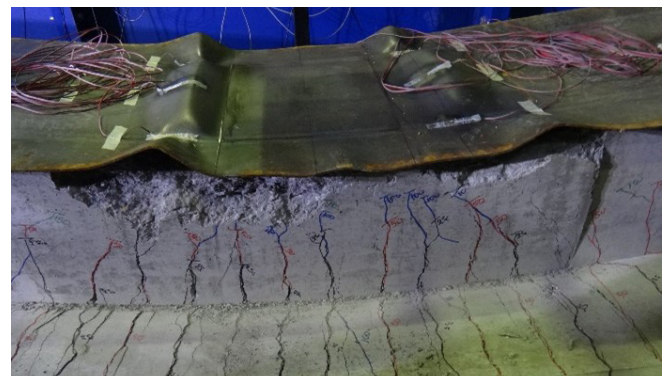
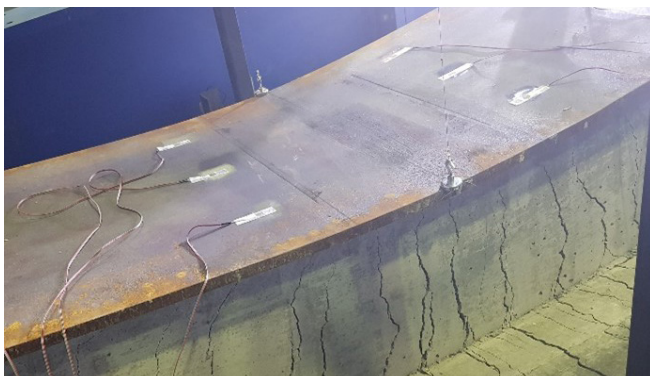
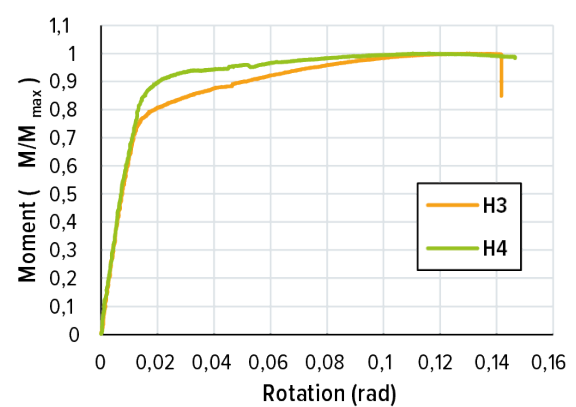
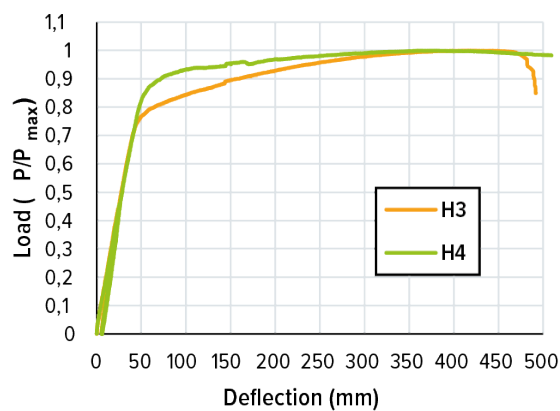


FIGURE 12. TYPE 4 SPECIMENS UNDER NEGATIVE BENDING (HOGGING BENDING)

DUCTILITY FACTOR

When we design a structure to sustain static loads, the primary structural elements must have sufficient resistance against the applied loads. In cases of extreme dynamic loads, the procedure is different. Earthquakes and generally extreme accidental situations are dynamic phenomena that occur rarely and last for only few seconds. Based on that, it can be easily understood that it would be uneconomical to design a structure to behave elastically in an extreme scenario and not take advantage of its ability to acquire a plastic behavior and deform plastically without losing its strength and its stiffness. In other words, it is more economical to allow the structure suffer minor damage rather than having an initially strong structure to be able to take all the load without any damage. Of course, appropriate measures must be taken to ensure that the damage is controlled and repairable. [4-7]

The factor that defines the deformation capacity of a structure and its structural elements and the size of the damage is called the ductility factor and indicates how much higher the maximum inelastic deformation d_m is in relation to the yielding deformation d_y :

$$\mu = \frac{d_m}{d_y}$$

The maximum value of factor μ depends on two basic factors:

- **The material of the structure.** Systems using ductile materials (structural steel) are allowed to develop larger values of factor μ than systems built with brittle materials (masonry, concrete).
- **The static system.** The more restrained degrees of freedom one structure has, the better its behavior is. This is because a local failure, generally, will not pose a collapse risk for the whole structure due to the redistribution of the loads and the remaining strength of the elements that are not severely damaged. On the contrary, isostatic constructions do not have “safety valves” and a failure of one element can lead to a collapse. Consequently, the ductility factor is highly related to the nature of the project and the use of the structure, and it is a matter of the collaboration and connection between all the structural elements assembling the structure and not of the beam’s behavior alone.

The desired ductility is finally defined by the designer according to the instructions and the limitations provided by the Eurocodes. The ductility factor can be described in terms of displacement or rotation (curvature). Higher ductility values mean bigger inelastic deformations and thereby a more economical design.

More specifically, the seismic design rules for dissipative composite structures aim at the development of reliable local plastic mechanisms (dissipative zones) in the structure and of a reliable global plastic mechanism dissipating as much energy as possible under the design earthquake action.

Earthquake resistant composite buildings shall be designed in accordance with one of the following design concepts:

- Concept a) Low-dissipative structural behavior.
- Concept b) Dissipative structural behavior with composite dissipative zones;
- Concept c) Dissipative structural behavior with steel dissipative zones.

Design concept of a structure	Structural ductility class	Required cross-section class
Concept a) Low-dissipative structural behavior	DCL (Low)	1, 2 or 3
Concept b) or c) Dissipative structural behavior	DCM (Medium)	1 or 2
	DCH (High)	1

TABLE 1. DESIGN CONCEPTS RELATED TO DUCTILITY CLASS AND CROSS-SECTION CLASS



In order to calculate the ductility of each tested beam the design plastic moment $M_{pl,Rd}$ was calculated. Ductility factor μ is part of the $M_{pl,Rd}$ line between two intersection points with the experimental curve (figure 14).

The calculated ductility and the cross-section class of each specimen are presented in table 2.

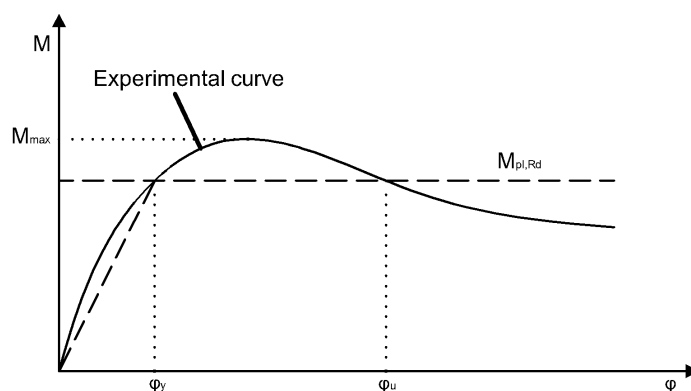


FIGURE 13. CALCULATION OF DUCTILITY FACTOR μ

Specimens	Ductility factor	Cross-section class	Specimens	Ductility factor	Cross-section class
Type 1			Type 3		
S2	1.37	Class 2	S6a	8.24	Class 1
S3	3.00	Class 2	S6b	8.00	Class 1
S4	3.09	Class 2	S7	8.47	Class 1
S5	3.37	Class 2	S8	10.72	Class 1
Type 2			H1	6.90	Class 1
S1	5.26	Class 1	H2	9.20	Class 1
S11	9.34	Class 1	Type 4		
S12	5.19	Class 1	S9	13.84	Class 1
S15	12.32	Class 1	S10	13.91	Class 1
H5	7.78	Class 1	H3	10.56	Class 1
H6	10.62	Class 1	H4	11.85	Class 1
H7	4.39	Class 1			
H8	5.64	Class 1			

TABLE 2. DUCTILITY VALUES AND CLASSIFICATION OF SECTIONS

It should be noted that all tests of Types 2, 3 and 4 stopped at a deflection approximately equal to 450 mm with no strength softening because the maximum stroke of the actuator was reached. This means that even higher deflection values could be reached before failure.

SIMULATION OF THE RESULTS WITH THE USE OF FINITE ELEMENT METHOD (FEM)

To shed more light into factors that could not be physically observed during the experiments and to deeper understand every aspect of the overall behavior of DELTABEAM®, a 3-dimensional model was created for each specimen using the Finite Element Method [8]. This paper presents the results of an example analysis of one beam. As can be observed in the figures 16 and 17, high attention was given to the accurate and detailed construction of the models. The high collaboration of the average load-deflection (figure 14) and average load-strain curves (figure 15) between the experimental and the calculated results as well as the realistic deformed shape (figure 18), prove the validity and the accuracy of the FE model. Some indicative images of the stresses and strains of the steel beam are following (figures 19 - 20) accompanied by the correct prediction of the local buckling on the bottom steel plate in the relative specimens (figure 21).

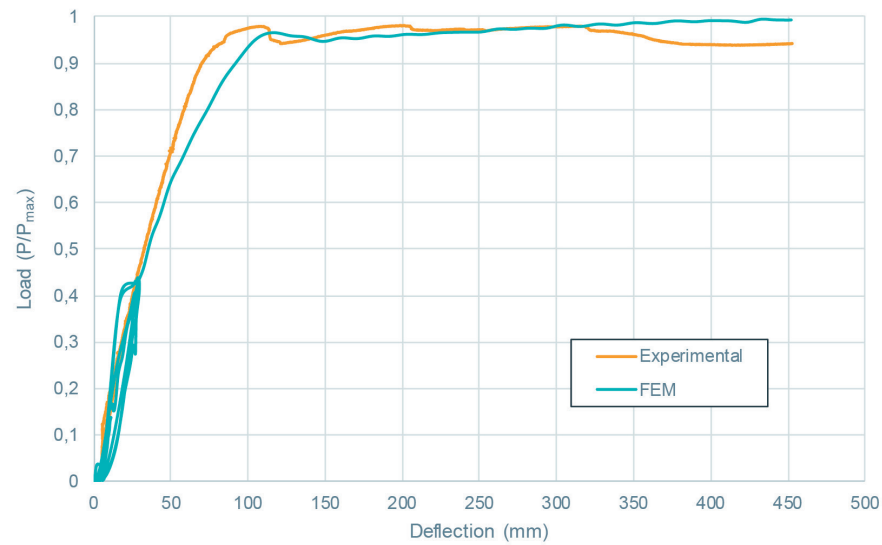


FIGURE 14. COMPARISON OF LOAD- DEFLECTION CURVES FOR EXPERIMENTAL AND ANALYTICAL RESULTS

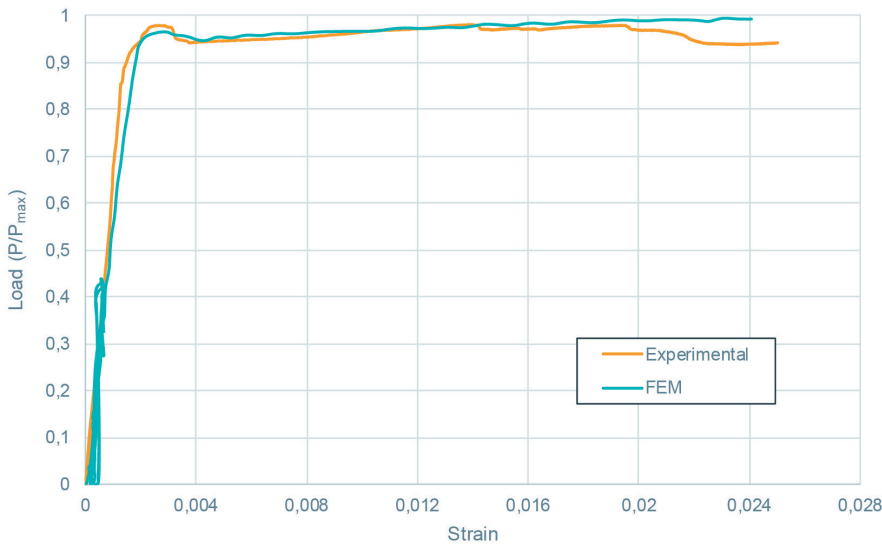


FIGURE 15. COMPARISON OF LOAD- STRAIN CURVES FOR EXPERIMENTAL AND ANALYTICAL RESULTS

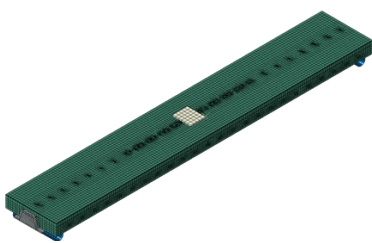


FIGURE 16. 3D MODEL OF TYPE 3 SPECIMEN

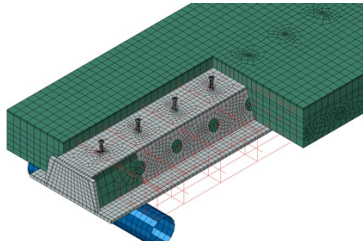


FIGURE 17. DETAIL OF THE 3D MODEL

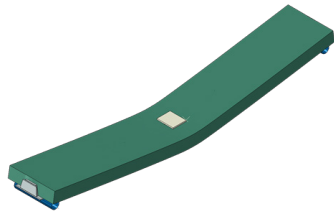


FIGURE 18. DEFORMED SHAPE

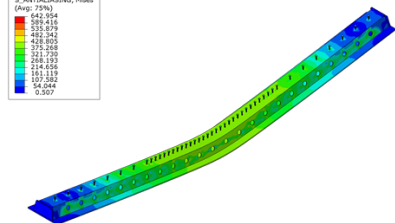
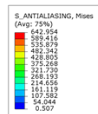


FIGURE 19. VON MISES STRESSES OF THE STEEL PART

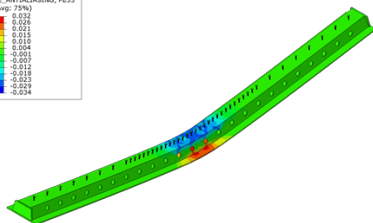
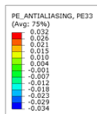


FIGURE 20. PLASTIC STRAINS ON THE STEEL PART

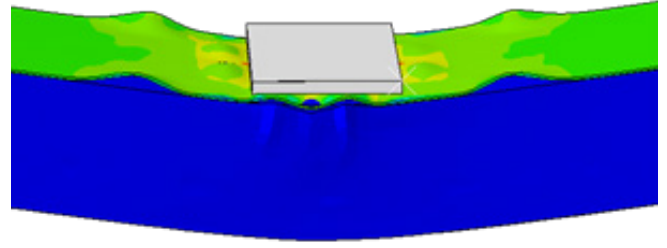
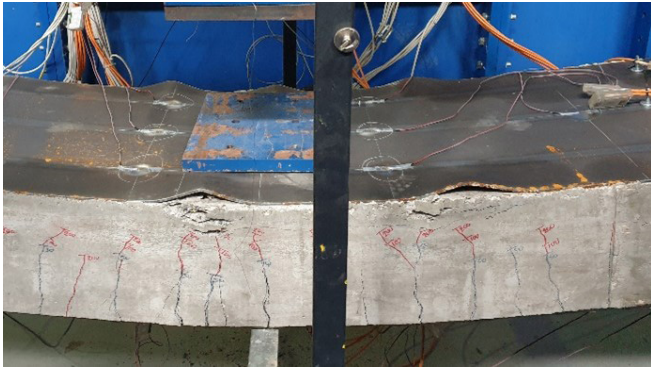


FIGURE 21. SIMULATION OF THE LOCAL BUCKLING ON THE BOTTOM STEEL PLATE

CONCLUSIONS

Facing the challenges of a safer and more economical design of structures against extreme situations, we at Peikko begun an extensive research project in order to prove the advantages of DELTABEAM® as a leading-edge solution in precast constructions. The project consists of three parts: i) Bending behavior under positive moments (Sagging), ii) Bending behavior under negative moments (Hogging), and iii) Design and creation of a moment beam-to-column connection. For the first and second part, twenty-two (22) full-sized DELTABEAMS® were tested under three-point positive and negative bending loads in order to assess their flexural behavior. The results showed that DELTABEAMS®, in conjunction with proper steel reinforcement, offer an extremely ductile behavior. The slips between concrete and steel beams were very small and the integrity of the specimens was maintained up to the end of the tests despite large deflections. Furthermore, the test revealed that, in contrast with the commonly used composite beam cross-sections, properly reinforced DELTABEAM® can maintain its load bearing capacity long after the appearance of local buckling in the plates under compression, due to its ability to redistribute the stresses to alternative load paths in the cross-section. This beneficial structural response indicates that properly reinforced DELTABEAM® can be implemented by the designers not only for typical ultimate state design but also for extreme cases, such as progressive collapse and earthquakes. Designing tools and technical documents will also be published after the completion of the project.

REFERENCES

- [1] Peikko Group Corporation (2014), DELTABEAM® Slim Floor Structure with Integrated Fireproofing - Technical Manual.
- [2] Peikko Group Corporation (2019), PCs® Corbel, Hidden Corbel for Supporting Beams - Technical Manual.
- [3] Kyriakopoulos P., Peltonen S., Vayas I., Spyarakos C. and Dasiou M., "Enhancement of ductility in shallow floor composite beams". 16th European Conference on Earthquake Engineering, Thessaloniki, 2018
- [4] CEN (European Committee for Standardization). (2006). Eurocode 1: Actions on structures - Part 1-7: General actions - Accidental actions, EN 1991-1-7:2006.
- [5] CEN (European Committee for Standardization). (2005). Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings, EN 1993-1-1:2005
- [6] CEN (European Committee for Standardization). (2004). Eurocode 4: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings, EN 1994-1-1:2004
- [7] CEN (European Committee for Standardization). (2004). Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, EN 1998-1:2004.
- [8] ABAQUS Theory Manual, "Version 2018," Dassault Systemes, 2017.





A faster, safer, and more efficient way to design and build

Peikko is a leading global supplier of slim floor structures, wind energy applications and connection technology for precast and cast-in-situ. Peikko's innovative solutions offer a faster, safer, and more efficient way to design and build.

www.peikko.com

