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A new developed approach for EDL induced from a single concentrated force

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Abstract. In this study, it is presented that a new developed approach for equivalent area-distributed loading (EADL) induced from a single concentrated force. For the purpose, a full scale 3D steel formwork system was constructed in laboratory conditions. A developed load transmission platform was put on the formwork system and loaded step by step on the mass center. After each load increment, displacement was measured in several crictical points of the system. The developed platform which was put in to slab of formwork to equivalently distribute the load from a point to the whole slab was constituted using I profiles. A 3D finite element model of the formwork system was analyzed to compare numerical displacement results with experimental ones. In experimental tests,difference among the displacements obtained from reference numerical model (model applied EADL) and main numerical model (model applied single load using a load cell via load transmission platform) is about %13 in avarage. Difference among the displacements obtained from experimental results and main numerical model under 30 kN single load is about %11 in avarage. The results revealed that the displacements obtained experimentally and numerically are dramatically closed to each other. It is highlighted from the study that the developed approach is reliable and useful to get EDL.

Keywords: 3D steel formwork system; equivalent area distributed loading; laboratory model; load transmission plafform

1. Introduction

There are many experimental and numerical studies related to structural behavior of steel or concrete structures under a concentrated force. The concentrated force is applied to the structure vertical or horizontal direction and generally load-displacements curves are obtained and the structural response is investigated (Camata *et al*. 2007, Arslan *et al*. 2008, Ozcan *et al*. 2009, Ng *et al*. 2012, Ke *et al*. 2014, Yılmaz and Şahin 2015). However, it is difficult to investigate the response under distributed area loading experimentally. Still, there are some experimental studies related to steel and concrete structures considering distributed area loading (Saito *et al*. 1992, Ye and Teng 2002, Foster *et al*. 2004, Grundy and Kabaila 2004, Bailey and Toh 2007, Ellouze *et al*. 2010, Cashell *et al*. 2011a, b, Scanlon and Suprenant 2011, Manos and Katakalos 2013, Santos *et al*. 2013).

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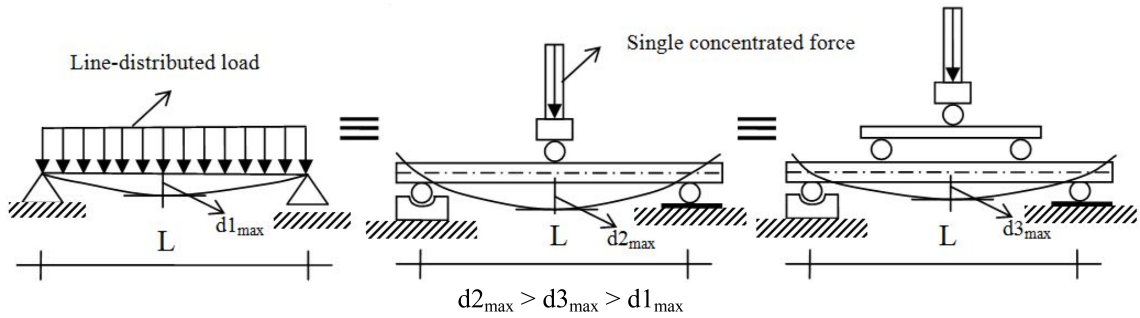

Fig. 1 Test set up related to a) line-distributed load, b) one-point loading and c) two-point loading

In these studies generally two methods have been used to distribute to loads to area from a concentrated force. One of these is to apply a resultant force in a point, the other one is to use sand bags throughout area. The displacement results obtained from these methods are acceptable to represent real distributed loading condition. However, the methods should not be suitable to obtain more realistic load-displacement curve due to requirement of applying loads in a controlled manner. Such that one-point loading or two-point loading are applied to represent equivalent line-distributed load (See Fig. 1). In Fig. 1, L is length of main span and d is the maximum deflection.

As shown in Fig. 1, the total load is the same resultant force for all three loading conditions, however the obtained displacements are different. So that it is very important to determine criteria for equivalent load. The test set up given in Fig. 1 is used in the literature and is presented in standards to obtain load-displacement curve for line-distributed loading. (Zhang and Dong 2012, Lois *et al*. 2013). But, the test set up is not represented in the standards for area-distributed loading. However main idea is similar as follows, the load is applied in a single point, and then it is distributed to a series of points on the area. The number and place of these points should be selected sensitevely to obtain so realistic deformation shape.

In this study, a new approach about equivalent area distributed loading (EDL) induced from a single concentrated force is presented. For the purpose, a full scale 3D steel formwork system was constructed in laboratory conditions. A developed load transmission platform was put on the formwork system and loaded step by step and displacements were measured in several critical points of the system. The load transmission platform was designed to obtain load-dsiplacement curve using “displacement” for equalization criteria instead of “load”, which was utilize to determine load capacity of formwork system. In the study firstly conversion of distributed loading to a series of concentrated loads is presented. Then it is mentioned about production of these concentrated forces from a single concentrated force source. Moreover experimental tests and computer based modeling are given, respectively. Lastly, the conclusions obtained from the experimental and numerical studies are taken place.

2. Equalization of area-distributed loading

A gradual approach is used for equalization of area-distributed loading. According this approach, firstly area-distributed load is converted to line-distributed loads and then the line-distributed loads are converted a series of concentrated forces. Here, equalization of line-distributed loading is presented by two steps as follows:

- It is decided to how many concentrated forces are used and where these forces are replaced to represent line-distributed loading.
- The concentrated forces are calculated to based on the similarity of deformation shapes between line-distributed loading and a series of concentrated forces.

These two simple steps used for the equalization of line-distributed loading are illustrated in an example. For the example, a simple supported beam having a span of 6 m and flexural rigidity of 10000 kNm^2 is selected. Uniform line-distributed load of 3 kN/m is assumed acting on the beam. In the example firstly deformed shape of the simple beam is obtained (See Fig. 2). Then equivalent concentrated forces are calculated considering their locations on the beam. The values and the numbers of equivalent concentrated forces for their selected location are presented in Table 1. Moreover, deformed shape of the beam for each equivalent loading case is shown in Fig. 2.

Discretizations of line-distributed loading by the series of concentrated forces are realized to get so similar deformed shape (See Fig. 2). Discretization of area-distributed loading by line loads depends on boundary conditions of loading platform. In other saying, it is related to transmission of loading on one-way or two-way. The discretization of line-distributed loading is done linearly in the case of one-way loading transmission. Numerically, if compressive loading of 3 kN/m2 effects to area of 3×3 = 9 m^2, it can be represented by three line-distributed loading of 3 kN/m. However, the value of the line loads can change based on location of line loading for two-way

Table 1 Determination of a series of concentrated forces

	Distances of loading points (m) on the beam					
Numbers of loading point	1	2	3	4	5	8
1	3.00	2.40	1.79	1.17	0.54	0.17
2		3.60	3.00	2.40	1.79	0.90
3			4.21	3.60	3.00	1.17
4				4.83	4.21	2.40
5					5.46	3.60
6						4.83
7						5.10
8						5.83

	Values of concentrated forces on the loading points (kN)						
Numbers of loading point	1	2	3	4	5	8	*8
1	1.8750	1.0000	0.5774	0.3774	0.1646	0.0472	1
2		1.0000	0.9677	0.7742	0.5488	0.2500	5
3			0.5774	0.7742	0.9146	0.3333	7
4				0.3774	0.5488	0.6667	14
5					0.1646	0.6667	14
6						0.3333	7
7						0.2500	5
8						0.0472	1
Total	1.8750	2.0000	2.1225	2.3032	2.3414	2.5944	54

*8 Normalization of concentrated forces with respect to the minimum forces

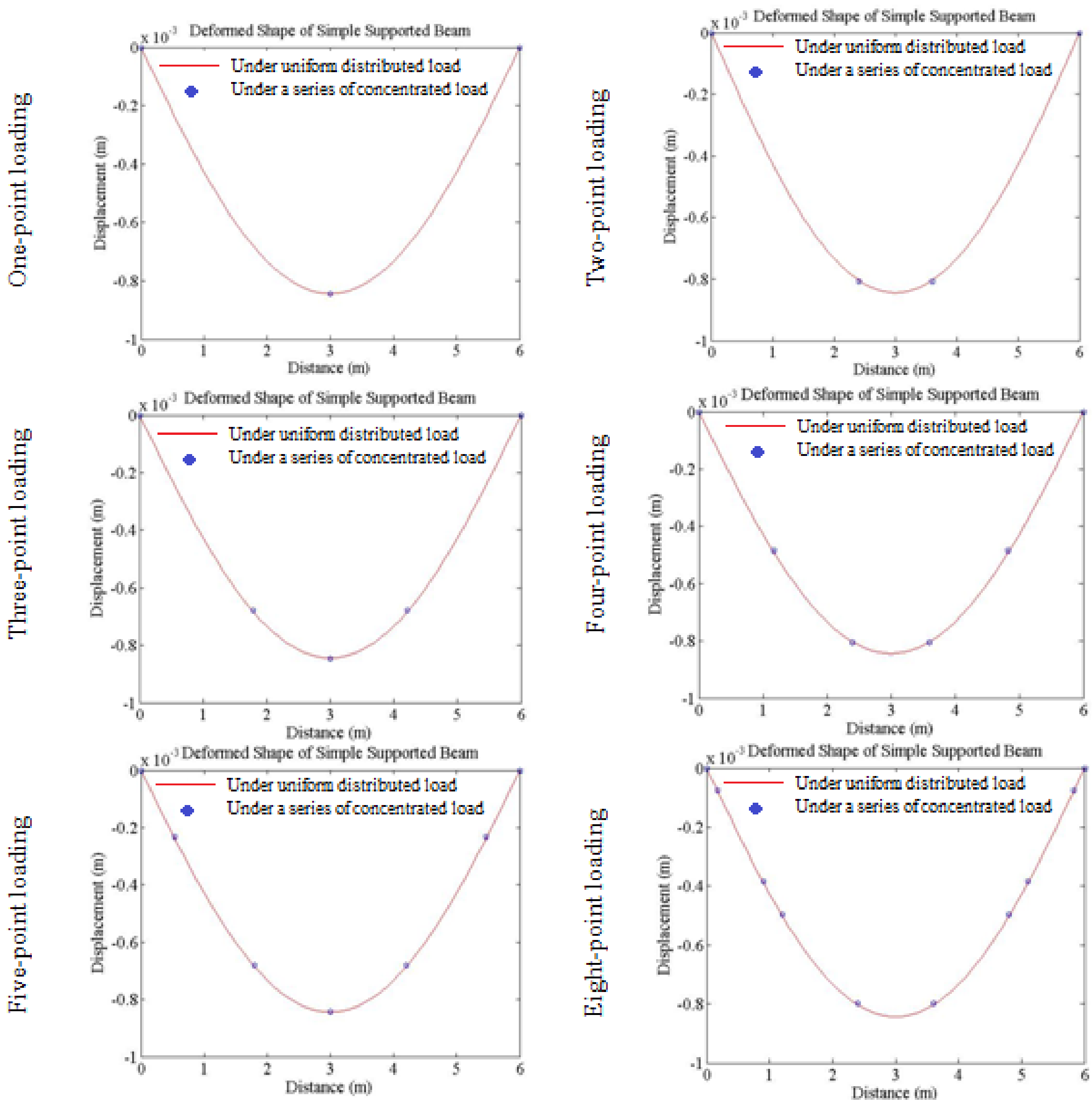

Fig. 2 Deformed shape of the beam for line-distributed loading and different equivalent loading cases

loading transmission. So, resultant force of line loading should be represented by equivalent concentrated forces. The schematic view of the discretization of area-distributed loading by line-distributed loading is illustrated in Fig. 3. In Fig. 3, the equalization of area-distributed loading by concentrated forces on one-way and two-way is shown step by step. In first step, the area-distributed load is converted to a resultant force. In second step, the resultant force is converted to line-distributed load in the related way. Each line-distributed load is converted a series of concentrated forces in the third step.

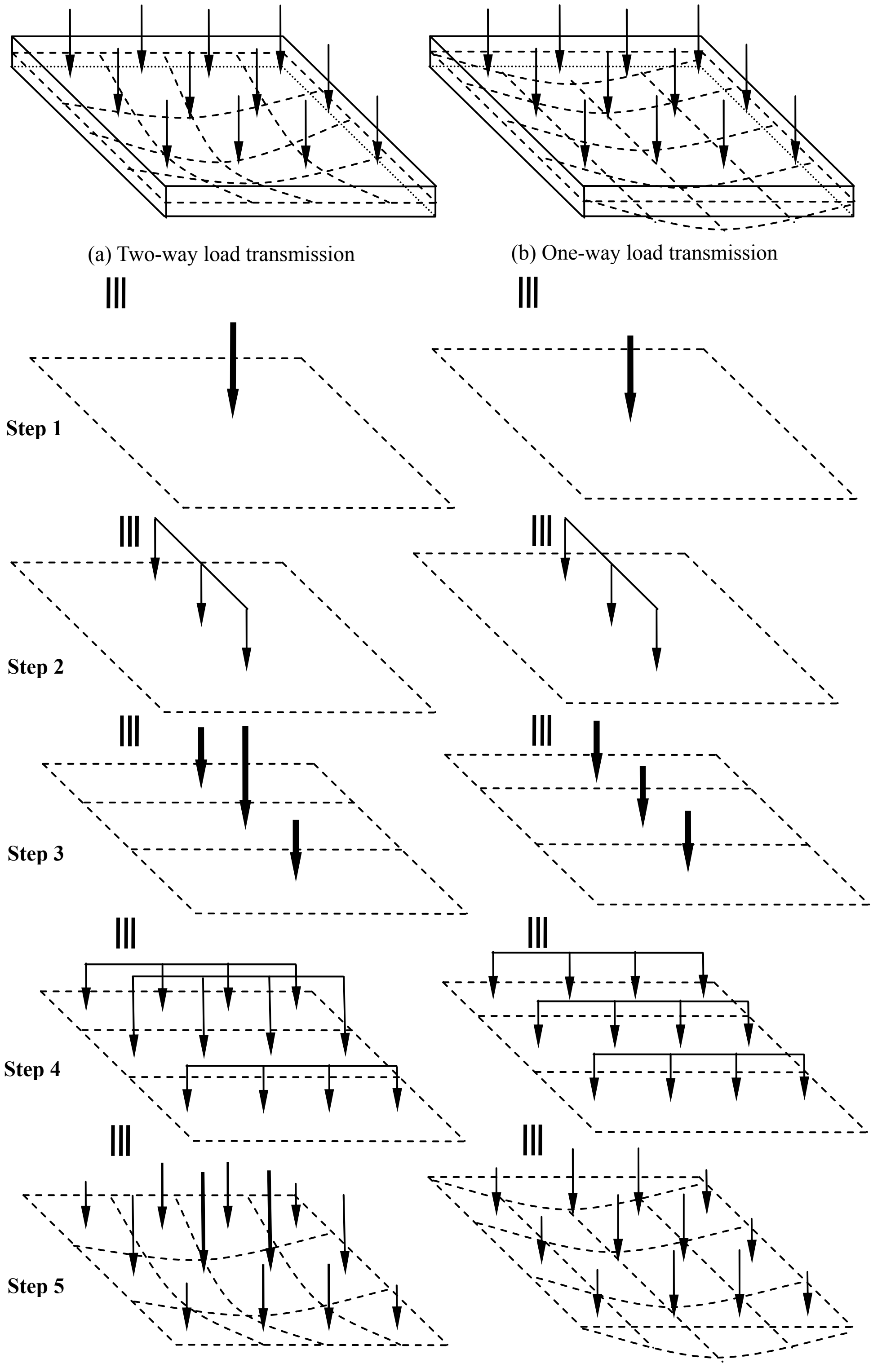

Fig. 3 Shematic view of transmission of area-disributed loading

2.1 Determination of a series of concentrated forces from a concentrated force

Area-distributed loading can be represented by the series of forces as mentioned above. But it is problem gives that how these forces will be product from a single concentrated force source. This part of the study details about the production of these force from the single load source, which is explained by two-point loading test. In a test set up, a single concentrated force applied to mid-span of the main beam system is converted two concentrated force, and these forces are transmitted to beam. (See Fig. 4). In the test, the reaction forces of the beam are the same for both of loading condition. The other complex example is related with load transmission with production of concentrated forces explained in Fig. 5. In the example, eight concentrated forces are produced from a concentrated force source using a profile platform. The values of a series of concentrated force are related to location of the load source on the main beam and application point of the series is related to location of platform elements on the beam. The following steps are considered in the Fig. 5, respectively. A concentrated force of 54 unit as load source is transmitted to eight concentrated forces with different values on level 6. Each transmitted force and its location are set up for each level. As seen in Fig. 5, the level 4 has a special part on the platform. In forth level, load transmission is provided from not only lateral profiles but also vertical profiles. Thus some of forces are transmitted to sixth level instead of fifth level. For example, concentrated forces of 7

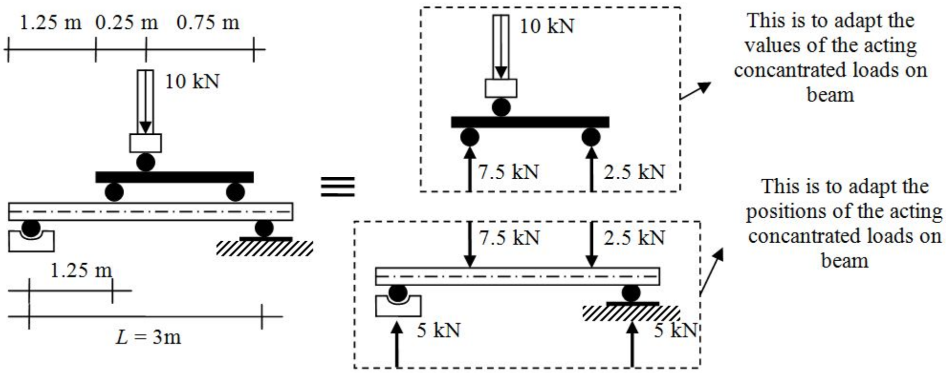

Fig. 4 Production of two concentrated forces from a single concentrated force

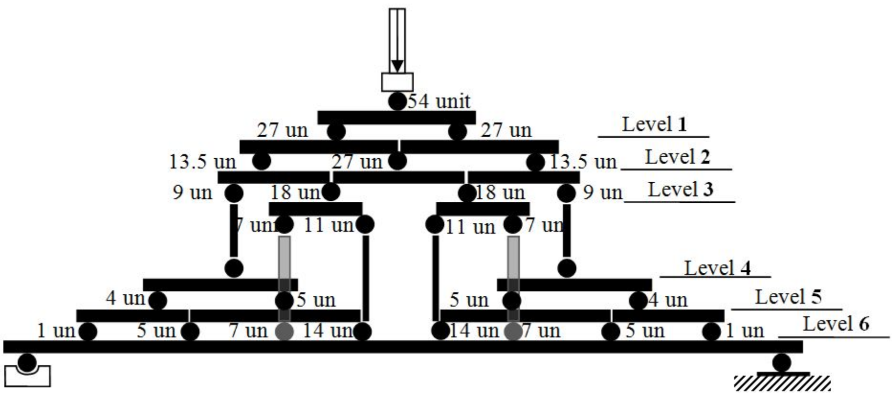

Fig. 5 Production of eight concentrated forces from a single concentrated force

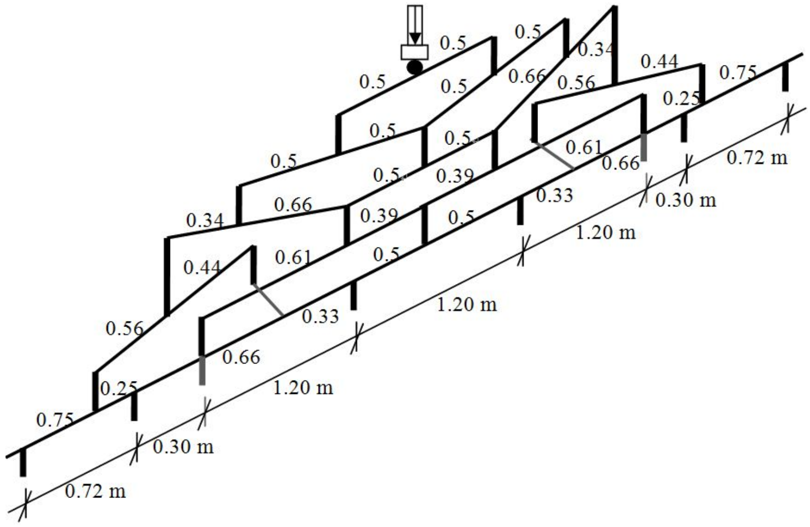

Fig. 6 Perspective of application about production of eight concentrated forces from a single concentrated force

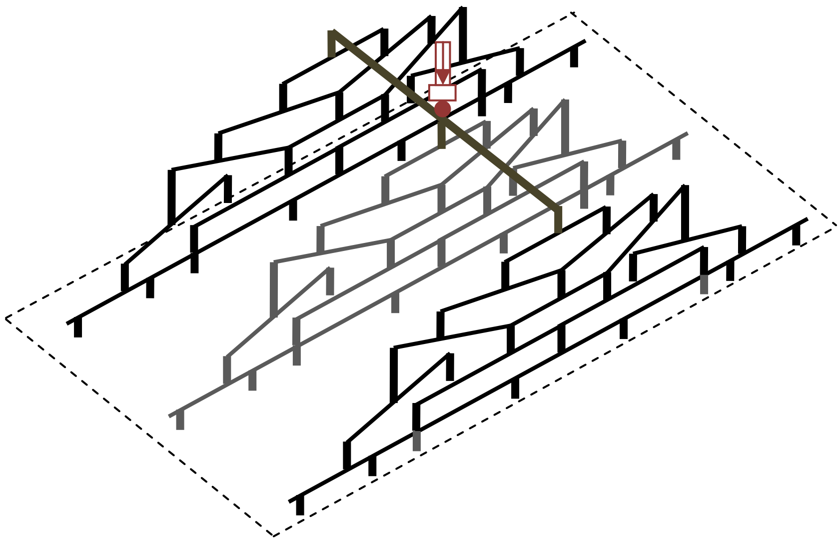

Fig. 7 Perspective of application about production of twenty four concentrated forces from a single concentrated force using six levels platform

unit in forth level is transmitted to sixth level directly. A similar transmission is seemed from third level to fifth level. To set up like a platform is very difficult due to lateral and vertical elements. It is necessary to locate the vertical element in some cases to avoid the overlap of these elements. More suitable and more applicable set up platform is drawn in Fig. 6 schematically. In Fig. 6, load transmission is provided by lateral and vertical profile elements with five levels. These elements connect to each other as pinned. Here, a single concentrated force source is transformed to equivalent line-distributed loading (ELDL) through one-way which consist of a series of

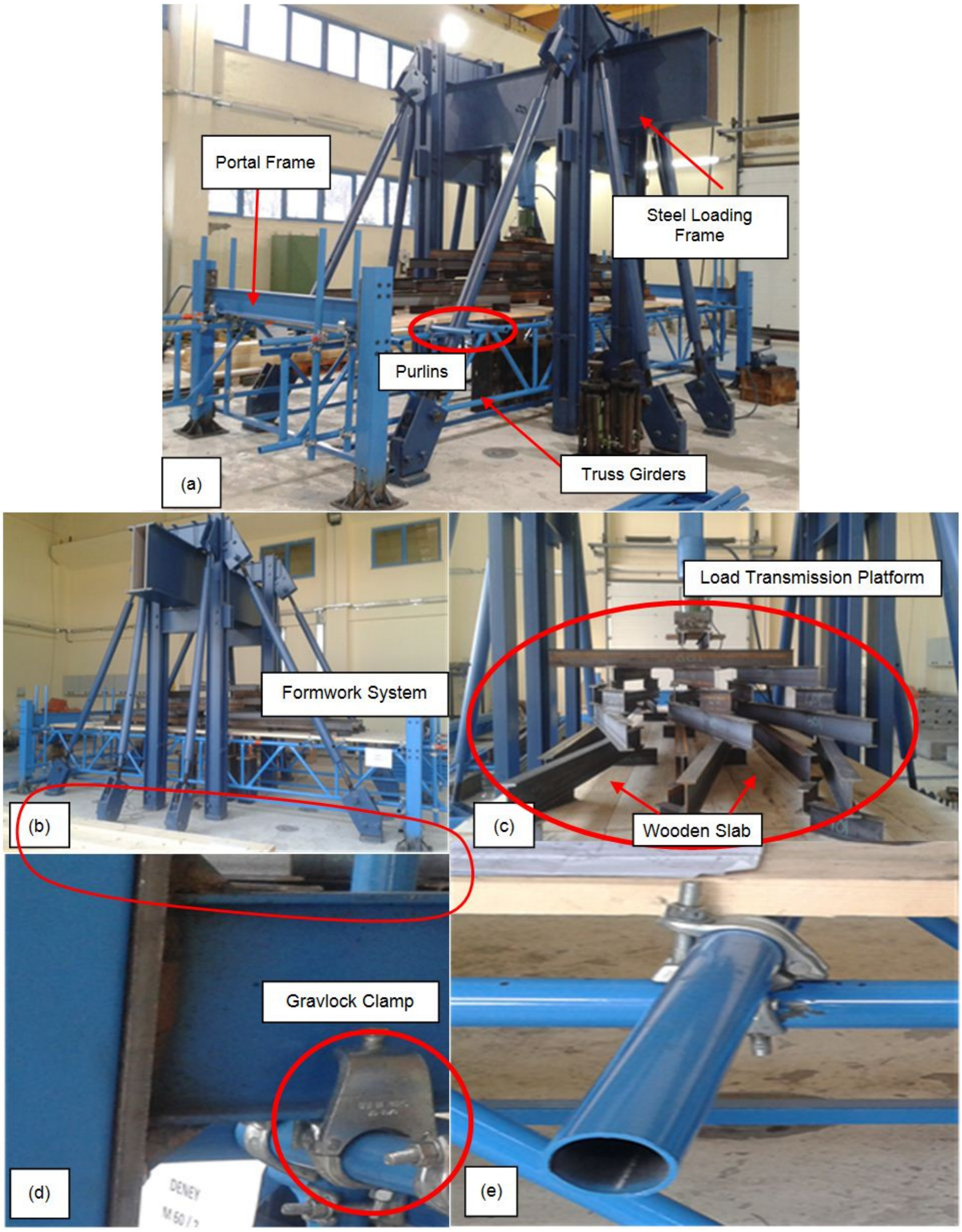

Fig. 8 (a) Perspective; and (b) left side view of test set-up and steel loading frame; (c) front view of load transmission platform; (d) front view of pin-suported connection between truss girder and portal frame; and (e) left side view of pin-suported connection between purlin and truss girder

concentrated forces along a line. Equalization of area-distributed loading with one-way single load series is demonstrated in Fig. 7. The load transmission is provided with six levels in Fig. 7.

2.2 Idealizations and assumptions on the production of load series

Some idealizations and assumptions are necessary on the production of load series. Therefore, some errors happen during transformation of area-distributed loading to series of concentrated forces. These errors can be explained as follow:

- Rounded values of the concentrated forces in equivalent loading obtained from the concentrated force,
- Locations of concentrated forces,
- Transmission errors during the application of test set up due to profile elements. These elements transmit force to overlap area instead of point. (See Fig. 8). For example, in Fig. 8, concentrated force is distributed along area bottom area of profiles on last level.
- Another error source may induce from the height between concentrated force source and slab of formwork system. The height can create stability failures.

The profile elements must be taken place as transmitting the load to all the slab of formwork system (Fig. 8(b)). So it should be considered in the test set up as seen in Fig. 8.

3. Tests of Eadl on the 3D steel formwork system

3.1 Description of the test set-up

In this study, a full scale 3D steel formwork system was constructed in laboratory conditions to apply the new approach of distributed loading over area induced from a concentrated force. The test set-up of EADL is illustrated in Fig. 8. In these tests, load capacity of a steel formwork system was investigated the steel formwork system consisted of a slab constructed by wooden board, purlins, plane truss girders, and portal frames. Load acted the slab whose dimensions were 6x1.6 m. The platform was supported to purlins which transmitted on loads to truss girders. The truss girders supported by two portal frames which transmitted on loads to base with rollers. The connections between the purlins and the truss girders (Fig. 8(e)) and between the trus girders and the portal frames (Fig. 8(d)) were pin-supported. The slab was freely replaced over purlins (Fig. 8(e)). The loading process is that a concentrated force source is provided by vertical hydraulic jack with capacity of 100 kN which connects to a steel frame loading system (Fig. 8(a)). The load obtained from the concentrated force was transmitted to the slab under favour of the developed platform (Fig. 8(c)).

3.2 Description of the load transmission platform on the test set-up

The transmission of the load to formwork system is performed as; the single concentrated force via transmission platform is distributed to formwork wooden slab, then the loads acting the slab are carried by purlins and are transmitted to truss girders, lastly the loads of the truss girders are taken from portal frames (see Fig. 8). According to transmission of the load mentioned above, the load is distributed to truss girders in one-way direction. So the main aim is to distribute the single concentrated force (source force) along the girders. To do this, it needs a load transmission platform which is provided many single concentrated forces with application points from a source load. The load transmission platform is constituted with five levels using I100 and I80 steel profiles. The steel profiles are selected considering value of the forces, the distances of

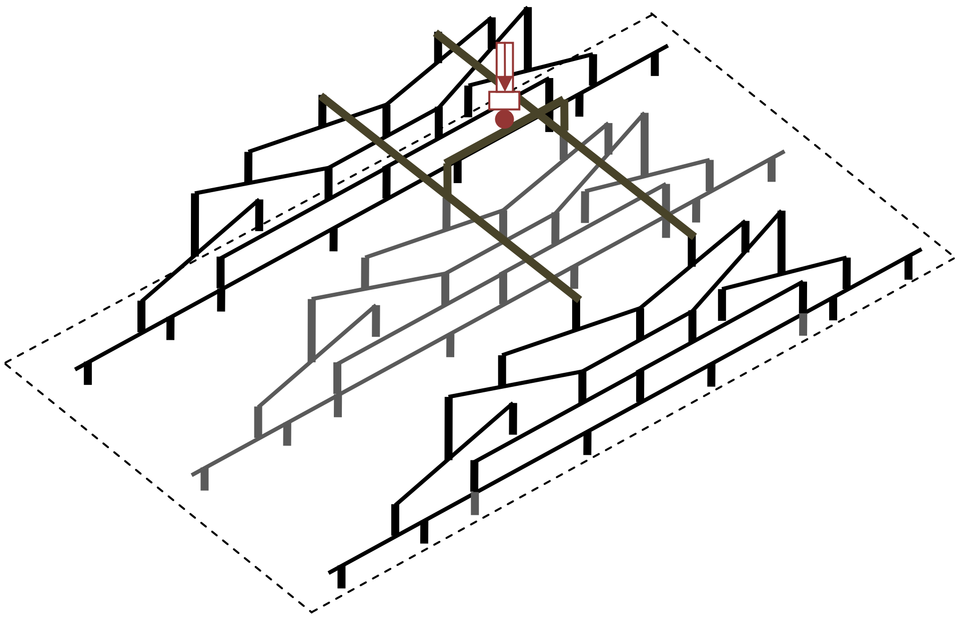

Fig. 9 Schematic view of the production of twenty four single concentrated forces from a single concentrated force source using five levels platform

transmission and their rigidities. There are two I100 profiles transmitting load to three load transmission part on the top level (first level). All pofiles are I100 at the bottom level (fifth level) of the platform. The location of the profiles are given in Fig. 6 in detail. The I80 profiles are placed to amid of the wooden board in the slab to distribute the load uniformly. The length of the profiles are selected as width of the wooden board. The levels are constituted with rigid beams and columns shown in Fig. 8(c). In Fig. 5, there are six levels for load transmission. In this study the loading transmission is provided with five levels (see Fig. 9). The difference comes from the last level. Here when producing the concentrated forces from the force source, it is aimed to transmit the forces to purlins.

In this study, 30 kN single load is totally applied to steel transmission platform and the displacements are measured using strain gauges. The self weight of the platform is 9 kN. So the measurements are written after emitting the displacements due to occurred self weight of the platform.

3.3 The loading of the test set-up

The load is not applied to formwork system as exceeding load capacity due to unknown of failure time and failure mode of the formwork system. But the formwork system is loaded as much as possible considering steel profiles and connections. Obtained load-displacement curves under these conditions are illustrated in Fig. 10. As seen in Fig. 10, there are five points where displacements are read. The first point is center point of the formwork system and it is below the wooden slab. Second and third points are below the midspans of purlins and forth and fifth points are below midspans of the truss girders. The displacements values on these critical points of the formwork system obtained under demanded single concentrated force of 30 kN and maximum single concentrated force of 49 kN are listed in Tables 2-3, respectively.

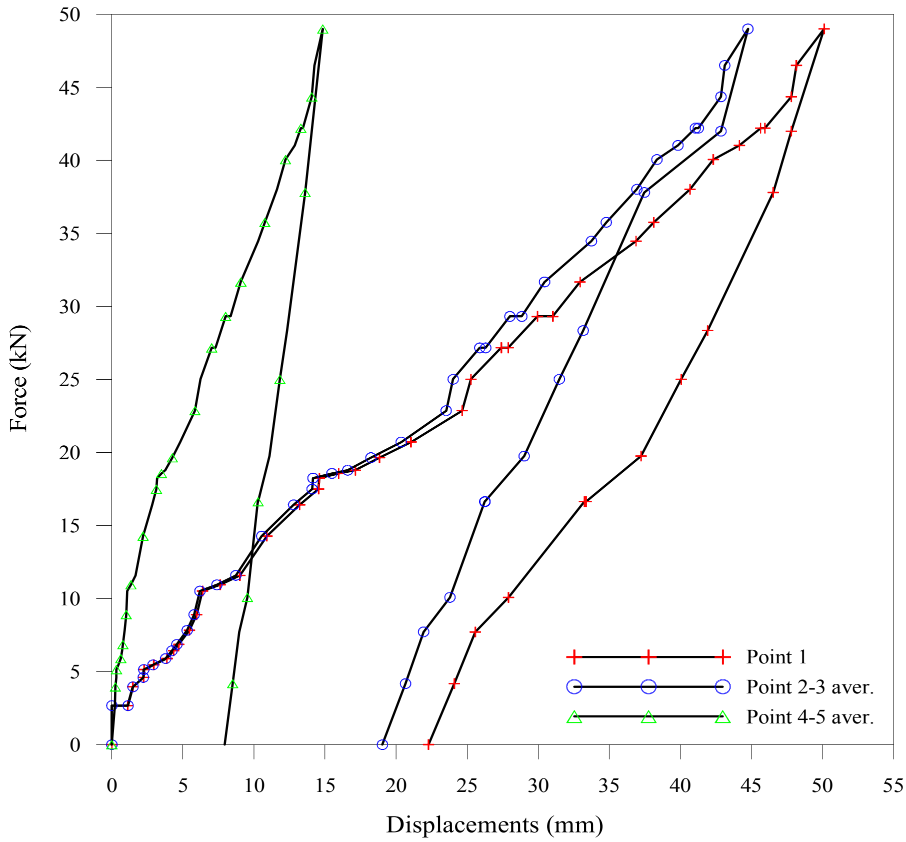

Fig. 10 Load-Displacements curves below the wooden slab (Point 1), purlins (Point 2-3 aver.), and truss girders (Point 4-5 aver.) of the formwork system

Table 2 Displacement values on the critical points obtained under 30 kN

Measurement point	Displacement (mm)
1. Point (Center of Wooden Slab)	31.59
Average of 2. and 3. Points (Midspans of Purlins)	29.31
Average of 4. and 5. Points (Midspans of Truss Girders)	8.57

Table 3 Displacement values on the critical points obtained under 49 kN

Measurement point	Displacement (mm)
1. Point (Midspan of Wooden Slab)	50.12
Average of 2. and 3. Points (Midspans of Purlins)	44.75
Average of 4. and 5. Points (Midspans of Truss Girders)	14.84

As seen in Fig. 10, the displacements under 49 kN occurred as 50 mm and 45 mm below the wooden slab and purlins, respectively. The value is nearly 15 mm on the truss girders. After unloading of the load, displacements obtained as 21 mm, 19 mm and 8 mm below the wooden slab, purlins and truss girders, respectively. This is not result from of the nonlinear behavior. The loading is applied in elastical region. Also the displacement values get near to zero when untightened the girder gravlock clamps. Ultimately, the formwork system is loaded with 9 kN transmission platform self weight and single load of 49 kN. This is nearly twice of the demanded load of 30 kN.

3.4 Numerical modeling of the formwork system and the load transmission platform

3D finite element model given in Fig. 11 of the formwork sysem and the load transmission platform are constituted using SAP2000 (2014) software. In the modeling, truss girders are fixed with pin and roller supports. Purlins have pin-connected joints with truss girders. Similarly, wooden slab is connected to purlins as pin. Also the wooden slab is not modeled as a single piece, it is modeled part by part as given in experimental setup. The sections of truss system, wooden board, and purlins are shown in Fig. 11. The elasticity modulus of wooden board is assumed as 9485 MPa in analytical studies, also the values is considered as 200000 MPa for steel truss and steel purlin.

In the study, a reference model is considered to check the EADL. In the reference model the load transmission platform is not modeled, so a concentrated force of 49 kN single load is applied to wooden slab as uniform area-distributed load. Then the main numerical model considering the load transmission platform is constituted in the software and a concentrated force of 49 kN load is applied to top of the platform and displacements are obtained. The displacements values on critical points for reference and main numerical models are listed in Table 4. As seen in Table 4, the difference between displacements values for reference and main models is averagely changed about %13. So it is considered that EADL provided with the load transmission platform is suitable.

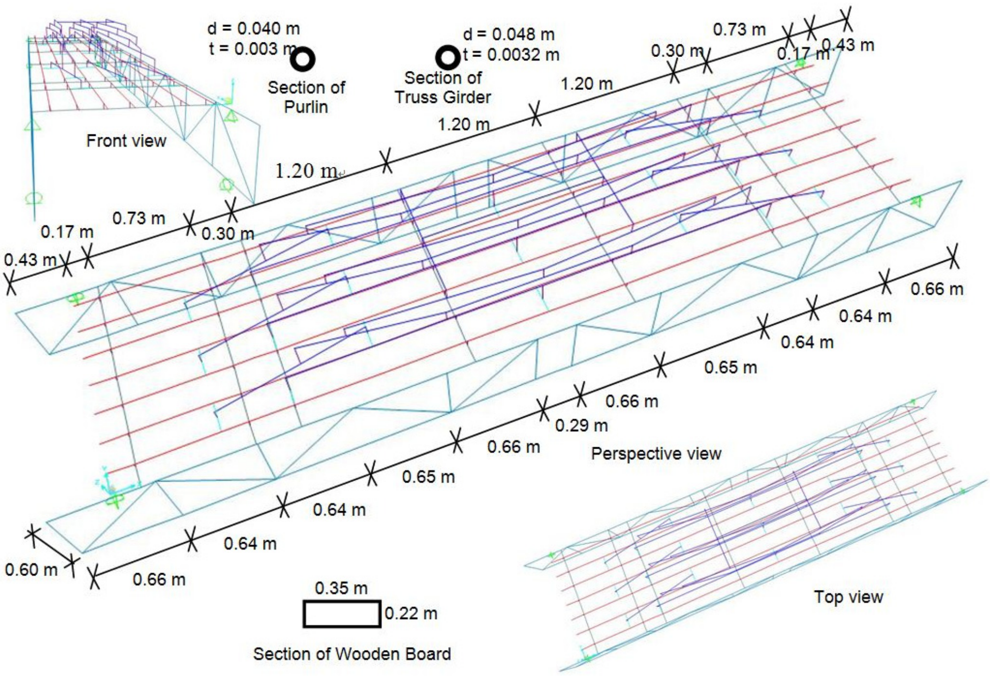

Fig. 11 3D finite element model of formwork system and load transmission platform

Table 4 Comparision of displacement values obtained for reference and main numerical model under 49 kN

Measurement point	Reference model displacement (mm)	Main model* displacement (mm)	Error (%)
1. Point (Below Wooden Slab)	41.20	47.30	14.80
Average of 2. and 3. Points (Below Purlins)	39.10	39.10	0.00
Average of 4. and 5. Points (Below Truss Girders)	10.20	12.90	26.50

* Formwork system and load transmission platform are assumed as weightless

After checking the main numerical model, displacements are obtained under concentrated forces of 30 kN and 49 kN, respectively and compared with experimental ones. (see Tables 5 and 6). As it is seen in Tables 5 and 6, difference among the displacements obtained from experimental results and main numerical model under 30 kN single load is about %11 in average. Difference among the displacements obtained from experimental results and main numerical model under 49 kN single load is about %10 in average.

Table 5 Comparision of displacement values obtained for experimental and numerical models under 30 kN

Measurement point	Experimental test* displacement (mm)	Numerical model** displacement (mm)	Error (%)	Numerical model*** displacement (mm)
1. Point (Below wooden slab)	31.59	28.90	8.50	38.70
Average of 2. and 3. Points (Below purlins)	29.31	23.90	18.50	32.20
Average of 4. and 5. Points (Below truss girders)	8.57	7.90	7.80	10.70

* Displacements are measured after replacing the load transmission platform
** Formwork system and load transmission platform are assumed as weightless
*** Formwork systems are assumed as weightless, but selfweight of load transmission platform is considered

Table 6 Comparision of displacement values obtained for experimental and numerical models under 49 kN

Measurement point	Experimental test* displacement (mm)	Numerical model** displacement (mm)	Error (%)	Numerical model*** displacement (mm)
1. Point (Below wooden slab)	50.12	47.30	5.60	57.10
Average of 2. and 3. Points (Below purlins)	44.75	39.10	12.60	47.40
Average of 4. and 5. Points (Below truss girders)	14.84	12.90	13.10	15.70

* Displacements are measured after replacing the load transmission platform
** Formwork system and load transmission platform are assumed as weightless
*** Formwork systems are assumed as weightless, but selfweight of load transmission platform is considered

4. Conclusions

In the paper a new developed approach is presented to transform a single concentrated force to EADL. For the purpose, both of experimental and numerical studies were performed. A steel formwork system was built and a load transmission platform using steel beam profiles put on the system to distribute load to all wooden slab. The platform was loaded with the single concentrated force in gravity direction and displacements were measured on the critical point of the system. The experimental study was compared with numerical studies. For the aim, a 3D numerical model was constituted in SAP2000 software and both of real and equivalent area distributed loading were applied to model and displacements were obtained. The following results and conclusions provided from the study are specified below:

- In experimental tests, the maximum displacements under 30 kN loading occurred as 31.59 mm, 29.31 mm, and 8.57 mm below the wooden slab, purlins and truss girders, respectively. The values under 49 kN loading were obtained as 50.12 mm, 44.75 mm, and 14.84 mm below the wooden slab, purlins and truss girders, respectively.
- In numerical analyses, the maximum displacements under 30 kN loading ignoring self weight of the system and platform occurred as 28.9 mm, 23.90 mm, and 7.90 mm below the wooden slab, purlins and truss girders, respectively. The values under 49 kN loading are obtained as 47.30 mm, 39.10 mm, and 12.90 mm below the wooden slab, purlins and truss girders, respectively.
- Difference among the displacements obtained from reference numerical model (model applied EDL) and main numerical model (model applied single load using a load cell via load transmission platform) is about %13 in avarage.
- Difference among the displacements obtained from experimental results and main numerical model under 30 kN single load is about %11 in avarage.
- Difference among the displacements obtained from experimental results and main numerical model under 49 kN single load is about %10 in avarage.
- The developed approach for EADL gives satisfactory results. So it is thought that the developed load transmission platform can be used both of experimental and numerical investigations.

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