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Critical Points of Prefabricated Reinforced Concrete Wall Systems of Multi-storey Buildings

J. Witzany, T. Čejka and R. Zigler

Abstract**—**With respect to the dissipation of energy through plastic deformation of joints of prefabricated wall units, the paper points out the principal importance of efficient reinforcement of the prefabricated system at its joints. The method, quality and amount of reinforcement are essential for reaching the necessary degree of joint ductility. The paper presents partial results of experimental research of vertical joints of prefabricated units exposed to monotonously rising loading and repetitive shear force and formulates a conclusion that the limit state of the structure as a whole is preceded by the disintegration of joints, or that the structure tends to pass from linearly elastic behaviour to non-linearly elastic to plastic behaviour by exceeding the proportional elastic limit in joints.Experimental verification on a model of a 7-storey prefabricated structure revealed weak points in its load-bearing systems, mainly at places of critical points around openings situated in close proximity to vertical joints of mutually perpendicularly oriented walls.

Keywords**—**dissipative energy, dynamic and cycling load repetitive load, working diagrams of joints

I. CRITICAL POINTS AND DISSIPATIVE ENERGY OF PREFABRICATED REINFORCED CONCRETE WALL SYSTEMS

The reliability and structural safety of prefabricated reinforced concrete wall systems exposed to extraordinary effects (explosion, fire, acts of terrorism) and dynamic effects (technical and induced seismicity, natural seismicity) rely on the plastic deformation mechanism of mainly the joints of load-bearing prefabricated members with simultaneous dissipation of energy. At this phase of the prefabricated load-bearing reinforced concrete wall systems' action, absorption of energy occurs, and the necessary condition at this phase of the bond's action (plastic action phase) is that the respective structural bond must not be completely eliminated from the load-bearing system. This presumes that the plastic deformation mechanism must prevail at critical points of the bearing system during the dissipation of energy. In the case of prefabricated wall systems, it is the vertical joints of prefabricated wall units exposed mainly to shear forces and the floor slab stiffness binding individual vertical wall members into a spatial load-bearing system that play the essential role in this perspective. Concerning the dissipation of energy, while applying the plastic shearing mechanism at these critical points it is vital to avoid a substantial decrease in the so-called return force and avoid any potential instabilities. With respect to the dissipation of energy through plastic deformation of joints of prefabricated wall units, efficient reinforcement of the prefabricated system at its joints is of principal importance. The method, quality and amount of reinforcement are essential for reaching the necessary degree of joint ductility.

The deformational characteristics of joints of bearing units may negatively affect the structural safety under repetitive and cyclic loading. In this respect, the major agents are, in particular, the vertical joints of load-bearing wall units that make up the fundamental parts of the load-bearing prefabricated system – load-bearing prefabricated walls. The degradation of vertical joints and their impaired stiffness in the phase of the appearance and development of cracks may be the cause of a severe drop in the stiffness of the bearing system resulting in the loss of its ability to resist external loading effects.

In accordance with ENV 1992-1-3:1994 the respective reinforcement (ties) should prevent the propagation of local damage and successive failure of the structure under extreme loading, such as the impact of an explosion, creating alternative ways of load transfer in the case of local damage. The degree and method of minimum vertical wall reinforcement are regulated by EN 1992 – 1 – 1. To assess local ductility along vertical joints of prefabricated units, the relevant code criteria must be met (Art. 5.11.3.4. EC 8).

Prefabricated planar systems are characterized by a deformation and failure mechanism under which planar elements shift in joints disintegrated by cracks, i.e. at so-called contact interfaces. Due to the fact that the deformations of elements as compared to the deformation of their joints are small, they can be solved for standard, mainly design loads, under the conditions of linear elasticity theory and planar stress state. We may, therefore, formulate an assumption that the limit state of the structure as a whole is preceded by joint disintegration, or that the structure tends to pass from linearly elastic behaviour to non-linearly elastic to plastic behaviour by exceeding the proportional elastic limit in joints (Fig. 1, [1]).

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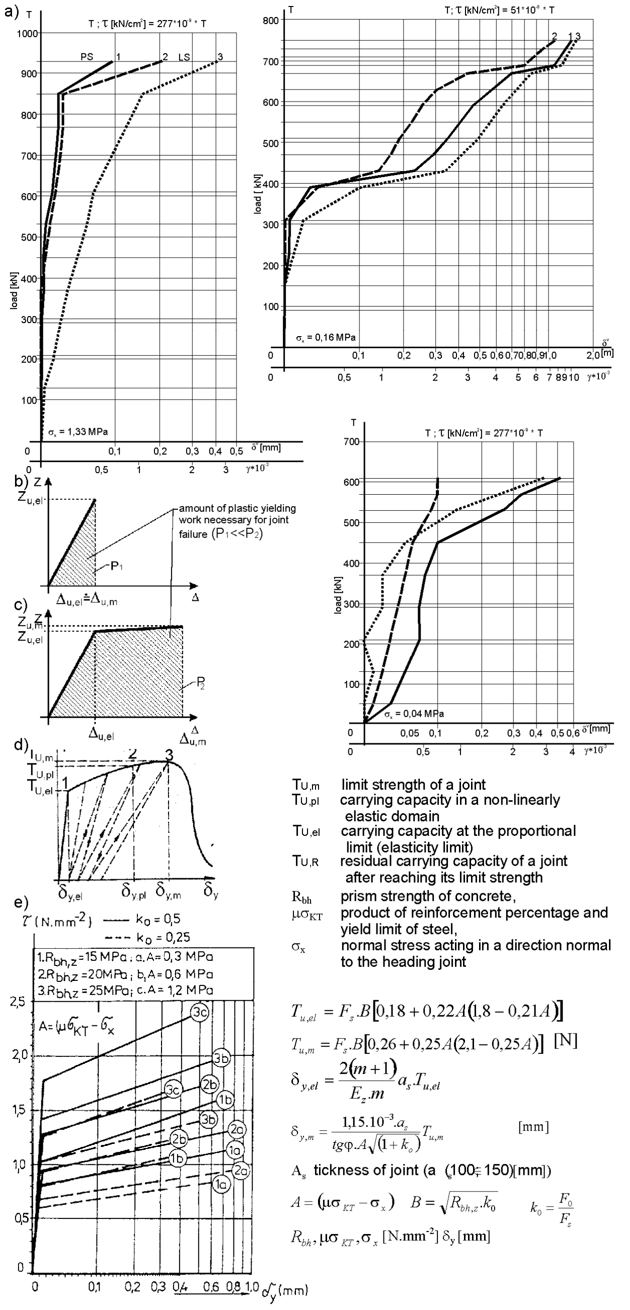


$T_{U,m}$	limit strength of a joint
$T_{U,pl}$	carrying capacity in a non-linearly elastic domain
$T_{U,el}$	carrying capacity at the proportional limit (elasticity limit)
$T_{U,R}$	residual carrying capacity of a joint after reaching its limit strength
R_{bh}	prism strength of concrete,
$\mu\sigma_{KT}$	product of reinforcement percentage and yield limit of steel,
σ_x	normal stress acting in a direction normal to the heading joint

$$T_{u,el} = F_s.B\left[0{,}18 + 0{,}22A\left(1{,}8 - 0{,}21A\right)\right]$$

$$T_{u,m} = F_s.B\left[0{,}26 + 0{,}25A\left(2{,}1 - 0{,}25A\right)\right] \ \text{[N]}$$

$$\delta_{y,el} = \frac{2(m+1)}{E_z.m} a_s.T_{u,el}$$

$$\delta_{y,m} = \frac{1{,}15.10^{-3}.a_s}{tg\varphi.A\sqrt{(1+k_o)}} T_{u,m} \qquad \text{[mm]}$$

A_s tickness of joint (a_s (100 ÷ 150)[mm])

$$A = (\mu\sigma_{KT} - \sigma_x) \quad B = \sqrt{R_{bh,z}.k_0} \qquad k_0 = \frac{F_0}{F_s}$$

$R_{bh}, \mu\sigma_{KT}, \sigma_x$ [N.mm^{-2}] δ_y [mm]

Fig. 1 Working diagrams of joints: a) working diagram, b) idealized working diagram of an unreinforced joint – without a non-linearly elastic behaviour domain, c) idealized working diagram of a reinforced joint with a prominent non-linearly elastic domain, d) characteristic working diagram of an unreinforced joint with bracing and residual loading capacity, e) theoretically established working diagrams of joints T x δ_y with cogs and for various values of R_{bh} and ($\mu\sigma_{KT}$ - σ_x) according to [1]

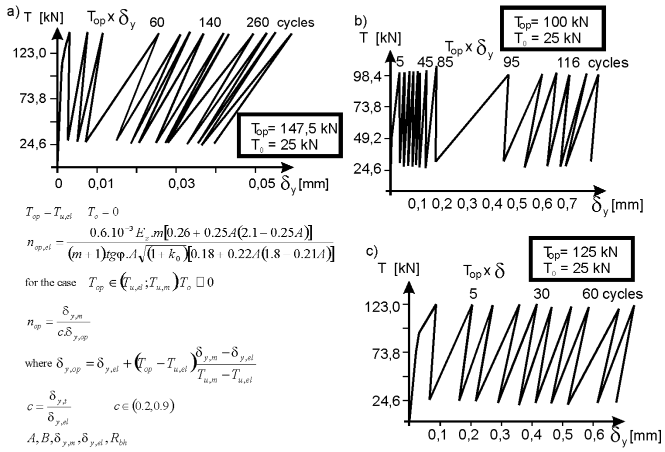
The experimentally determined values of relative shifts in relation to the joint width (i.e. 100 mm to 150 mm) around the proportional elasticity limit $\delta_{y,u}$, range between 2.10^{-2} mm and 1.10^{-1} mm. The permanent deformation $\delta_{y,t}$ after exceeding δ_u is 50 to 80 % of the total deformation δ_y, while the limit deformation of the vertical joint $\delta_{y,m}$ at reaching the limit load T_m is 0.6 to 2.5 mm. The total deformation in the domain of residual load-bearing capacity of the joint, i.e. after exceeding the ultimate bearing capacity T_m, may reach 10 to 25 mm. At this phase of action, the joint shows stiffness in the order of 10^{-2} and below as compared to the joint stiffness in the linearly elastic domain ($T \in (0\ ,\ T_m)$); also, having exceeded the load at the proportional elastic limit T_u, the joint stiffness falls to 10^{-1} - 10^{-2} of the initial joint stiffness value. This drop in stiffness affects the increments (decrements) of normal stresses in some units of the load-bearing system.

Apart from achieving more truthful design models of the bearing system, the introduction of physical dependences of joint behaviour also allows solving problems related to the assessment of a system with non-linearly elastic behaviour of joints of bearing elements exposed to the effects of emergency loading.

II. EXPERIMENTAL RESEARCH OF PLASTIC SHEARING MECHANISM UNDER LOADING WITH REPETITIVE SHEAR FORCE

The capacity of dissipative joints of prefabricated wall units, which represent critical chains (points) of the prefabricated load-bearing wall system in terms of its resistance to extraordinary effects and seismic loading, may be validated by means of inelastic cyclic testing where the so-called plastic shearing mechanism under loading with repetitive shear force is verified (EC 8).

The results of experimental tests (Fig. 2, [2]) manifested that the joints of concrete elements are extremely sensitive to the effects of variable repetitive and cyclic loading, the joint failure occurring due to cyclic loading amounting to 40 - 70% of the joint limit load. Time-related non-linear changes in joint properties, in relation to the loading history and plastification, may be of principal importance for the structural safety and serviceability of the bearing system in time.



$$T_{op} = T_{u,el} \qquad T_o = 0$$

$$n_{op,el} = \frac{0.6.10^{-3} E_z.m\left[0.26 + 0.25A(2.1 - 0.25A)\right]}{(m+1)tg\varphi.A\sqrt{(1+k_0)}\left[0.18 + 0.22A(1.8 - 0.21A)\right]}$$

for the case $T_{op} \in \left(T_{u,el} ; T_{u,m}\right) T_o \square 0$

$$n_{op} = \frac{\delta_{y,m}}{c.\delta_{y,op}}$$

where $\delta_{y,op} = \delta_{y,el} + \left(T_{op} - T_{u,el}\right)\dfrac{\delta_{y,m} - \delta_{y,el}}{T_{u,m} - T_{u,el}}$

$$c = \frac{\delta_{y,t}}{\delta_{y,el}} \qquad c \in (0.2, 0.9)$$

$A, B, \delta_{y,m}, \delta_{y,el}, R_{bh}$

Fig. 2 Experimentally established working diagrams of vertical joints; a) repetitive and cyclic loading of unreinforced joint, T_{op} = 147.5 kN, failure in 278th cycle; b) repetitive and cyclic loading of unreinforced joint, T_{op} = 98.4 kN, failure in 120th cycle ($\sigma_{x,m}$ = -0.07 MPa); c) repetitive and cyclic loading of unreinforced joint, T_{op} = 123 kN, failure in 84th cycle ($\sigma_{x,m}$ = -0.087 MPa) [2]

The number of cycles n_{op} of repetitive loading leading to failure is dramatically affected by so-called joint ductility, i.e. the range (domain) of non-linearly elastic joint behaviour, which mainly relies on the amount and type of reinforcement or prestress ($\mu \, . \, \sigma_{KT}$, $T_a \, . \, F_a \, \sigma_x$). The number of cycles n_{op} of repetitive loading by the force T_{op} depends on the magnitude of the force T_{op}. With the growing force T_{op} the number of cycles n_{op} leading to the joint failure decreases (Fig. 3a). The number of cycles of repetitive loading is also significantly affected by the magnitude of the force T_o permanently acting in the joint. With the growing interval (T_o, T_{op}) the number of cycles of repetitive loading leading to the joint failure decreases. The results of experimental research proved that mainly in the domain of low reinforcement ($\mu \, . \, \sigma_{KT} \in (0.1; 0.3)$ Nmm^{-2}) the joint prestress ($- \sigma_x$) may affect the number of cycles n_{op} more dramatically than reinforcement ($\mu \, . \, \sigma_{KT} = -\sigma_x$). This may be explained by the fact that reinforcement in the joint starts to act only under deformations approaching the value of δ_m. In this phase, the joint has already been damaged by diagonal cracks (Fig. 3b) and as a result of concrete disintegration in the vicinity of cracks (loosening of grains) shear stress is "poured" into the surroundings of the joint transverse reinforcement where – due to the "dowel-like" effect of reinforcement ("splitting" force around reinforcement) – the reinforcement successively tends to loosen.

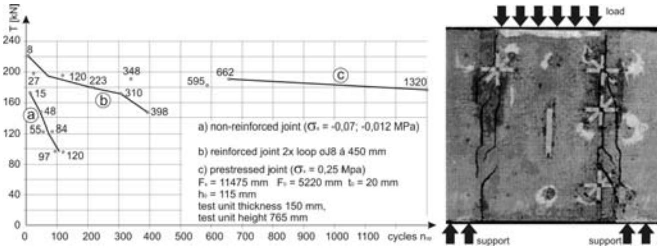


Fig. 3 a) Dependence of the number of cycles of repetitive loading n_{op} on the magnitude of the shear force T_{op} [2]; b) Characteristic failure of a vertical joint loaded by shear [1]

After exceeding the joint's proportional elastic limit (at least in one load cycle), repetitive – cyclic – effects cause gradual degradation of the joint, a gradual growth in deformations (strain) in joints leading up to a complete failure of joints (low-cycle fatigue, incremental collapse).

III. CONCLUSION

While assessing the resistance of prefabricated wall systems to extraordinary dynamic effects (caused e.g. by technical, induced and natural seismicity) potential degradation of joints due to cyclic deformations (loading) beyond the yield (proportionality) limit must be assessed which is caused by the system's response to external dynamic effects. The failure mechanism – collapse of the critical bond – occurs by reaching the limit deformation under repetitive (cyclic) loading with a force approaching the yield limit, not under limit loading – incremental collapse. This issue was the subject of experimental research performed within the Research Plan "Reliability, optimization and durability of building materials and structures", including research on a model of a 7-storey prefabricated load-bearing wall system assembled in 1:3 scale [3].

Repetitive loading of the experimental model was carried out by a pair of steel ties exerting an inclined force with horizontal and vertical components acting at the upper free end of the model. The vertical component stabilized the experimental model of the structure against tilting (exerting compressive stresses in bed joints and substituting the effect of the vertical load, Fig. 4, [4]). Experimental research was performed on a model of a 7-storey prefabricated planar system loaded by the combination of step-by-step monotonously growing static loads and repetitive loads. In the total of three load states, 27 monotonously growing static load stages and 24 dynamic stages were performed. Static loading was performed by a step-by-step monotonously growing load increasing from 10 to 30 kN acting on each tie. Once completed, static loading was followed by dynamic loading in a range of ca 80,000 vibrations with an oscillation frequency of 15 Hz between individual static cycles.

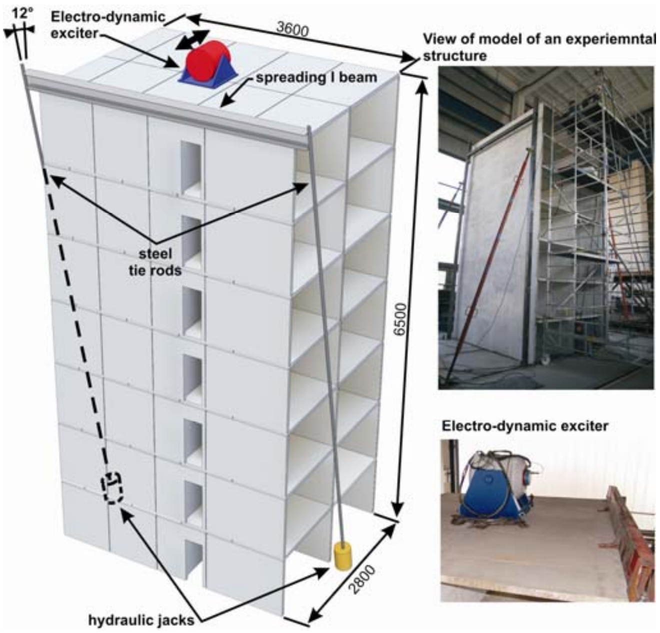


Fig. 4 Loading diagram of a model of an experimental structure with inclined forces exerted by steel ties; picture of the experimental structure and the mounted electro-dynamic exciter

The analysis and comparison of the experimentally determined increments of total and permanent deformations at the top of the experimental model in individual load cycles of the 1st, 2nd and 3rd states of loading for the case of a selected frequency value of 15 Hz (experimentally measured 1st and 2nd natural frequencies at the 7th storey level are $f_1 = 5.62$ Hz and $f_2 = 13.92$ Hz, while at the 4th storey level $f_1 = 5.37$ Hz and $f_2 = 13.92$ Hz) suggest a relatively low impact of dynamic effects on a gradual decrease in the stiffness of the load-bearing system resulting from joint degradation (appearance of structural cracks and their propagation in the joints of load-bearing units). The relatively high frequency of dynamic loading exerted by the electro-dynamic exciter with a very low oscillation amplitude to which the experimental model was exposed caused a slight increase in horizontal deformations $\varepsilon_{y,c}$.

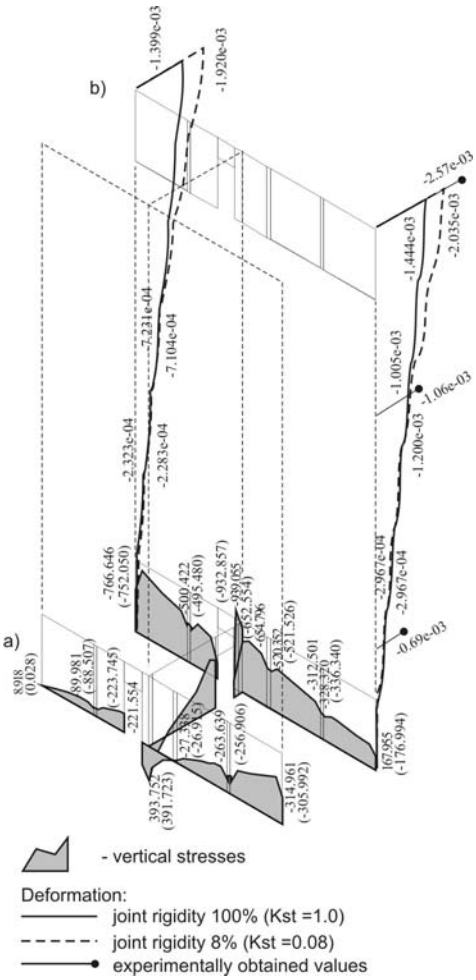


Fig. 5 a) Theoretically obtained course of vertical normal stresses σ_x due to the effect of loading by an inclined force 2 × 30 kN acting at the upper free end of the test structure, at the toe of the assembly at a level z = 0 ; b) The course of horizontal deformations (deflections) along the height of the test assembly at the point of the vertical joint of the longitudinal and transverse walls (same loading as in a).

The growth in the total and permanent deformations caused by the impact of repetitive gradually growing unidirectional loading during the 1st – 3rd state of loading, i.e. after 24 cycles, amounted to 82.5% and 387.5% respectively, as compared to the first load cycle of the 1st state of loading. The growth of the total and permanent deformations caused by the impact of dynamic loading in the 2nd state of loading, i.e. after 80 × 10^4 cycles with a high frequency and a very low amplitude, which amounted to 90.9% and 166% respectively, testified that at this stage the investigated effect of dynamic load did not cause stresses in the vertical joints of the wall units exceeding the limit of their linearly elastic action. Unlike dynamic loading with a high frequency, low-cyclic repetitive shear loading, where loading exceeding the proportional elastic limit of the T × δ relationship is reached in the vertical joints of wall units at least in some cycles (Fig.2), causes a progressive decrease in the joint stiffness with a subsequent, substantially more serious effect on a gradual decrease in the structural safety of the load-bearing system as compared to the dynamic effects caused by technical seismicity (e.g. effects of traffic, Fig.5) [4].Experimental verification revealed weak points in load-bearing systems, mainly at places of critical points around openings situated in close proximity to vertical joints of mutually perpendicularly oriented walls.

IV. SUMMARY

The experimental and theoretical research completed to-date has manifested a relatively high resistance of prefabricated wall systems of multi-storey buildings with discrete arrangements of reinforcement securing the joints between individual load-bearing prefabricated units at the floor slab level (Fig. 6) to the effects of common technical seismicity with a frequency spectrum of seismic response and a magnitude of seismic loading within the verified range. Analogical results, however, cannot be expected for the case of natural seismicity characterized, unlike technical seismicity, by a relatively low frequency in the order of units and large amplitudes.

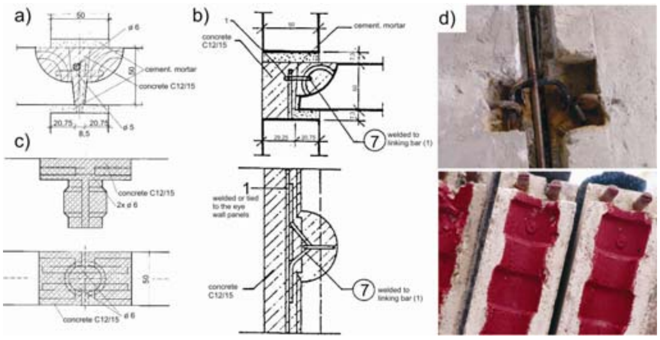


Fig. 6 Scheme of join of "wall – ceiling structure – wall" in the central part (a) and peripheral part (b) of the structure, c) scheme of vertical joint of wall elements, d) joint of wall and floor unit, linking bar, wall units faces coated with separation paint

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